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Rémus et al.

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[45] **Date of Patent:** **Feb. 4, 1986**

[54] **METHOD FOR REDUCING THE CONSUMPTION OF A STEPPING MOTOR AND DEVICE FOR CARRYING OUT THE METHOD**

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[73] Assignee: **Asulab S.A.**, Switzerland

[21] Appl. No.: **580,305**

[22] Filed: **Feb. 15, 1984**

Related U.S. Application Data

[63] Continuation of Ser. No. 345,952, Feb. 4, 1982, Pat. No. 4,446,413.

[30] **Foreign Application Priority Data**

Mar. 18, 1981 [CH] Switzerland 1826/81

[51] **Int. Cl.**^{4} **H02P 8/00**
[52] **U.S. Cl.** **318/696**; 318/685

[58] **Field of Search** 318/696, 685; 368/62, 368/76, 85, 157, 204, 219

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,340,946	7/1982	Kanno et al.	368/76

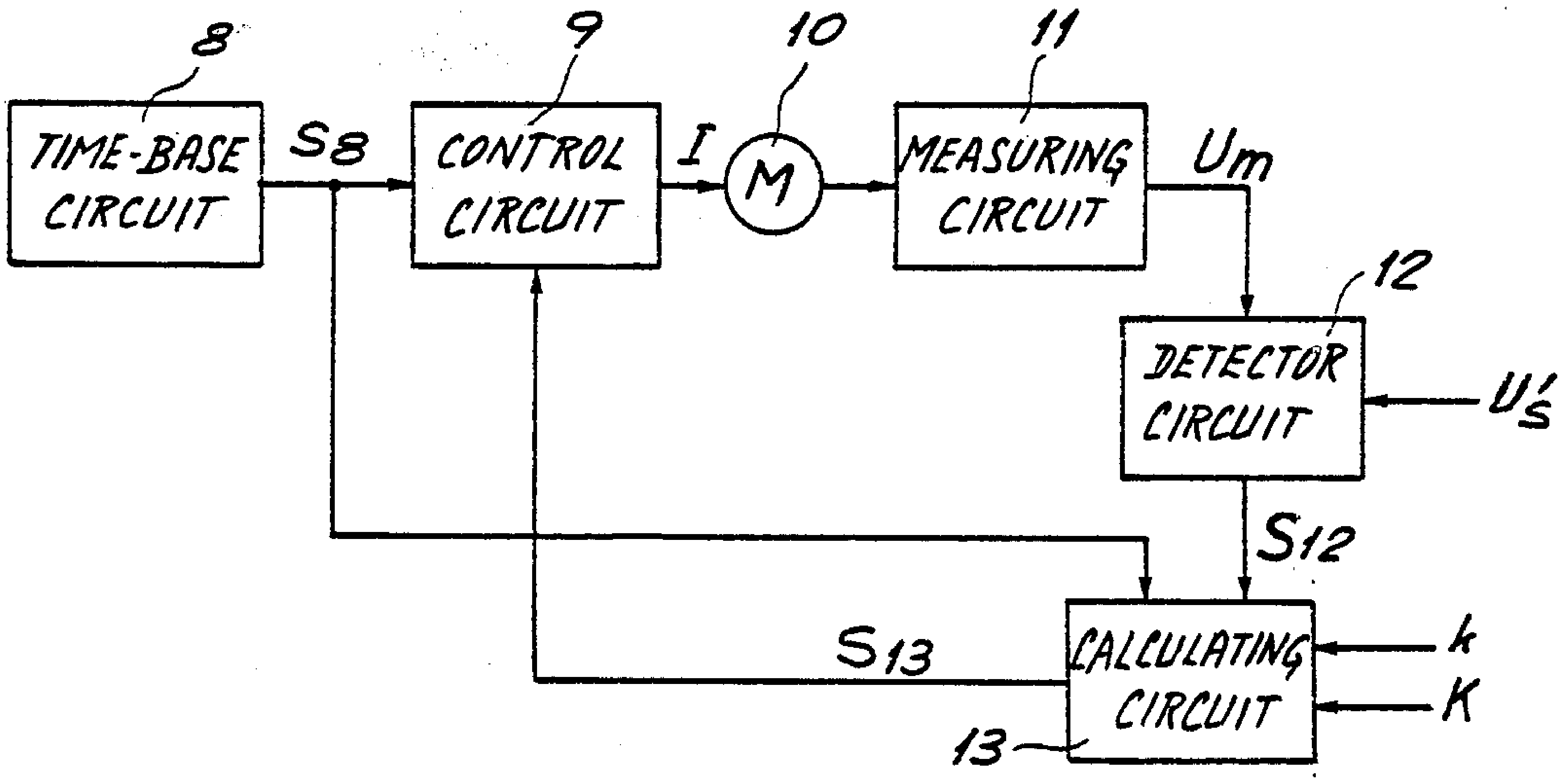
Primary Examiner—William M. Shoop, Jr.
Assistant Examiner—Saul M. Bergmann
Attorney, Agent, or Firm—Pollock, Vande Sande & Priddy

[57] **ABSTRACT**

The method comprises measuring the voltage induced during the driving pulse in the coil by rotation of the rotor, and interrupting the drive pulse in dependence on the measurement made.

The device for carrying out this method comprises a circuit for measuring the induced voltage, a circuit for comparison with a reference value and a circuit for calculating the duration of the drive pulse.

6 Claims, 18 Drawing Figures



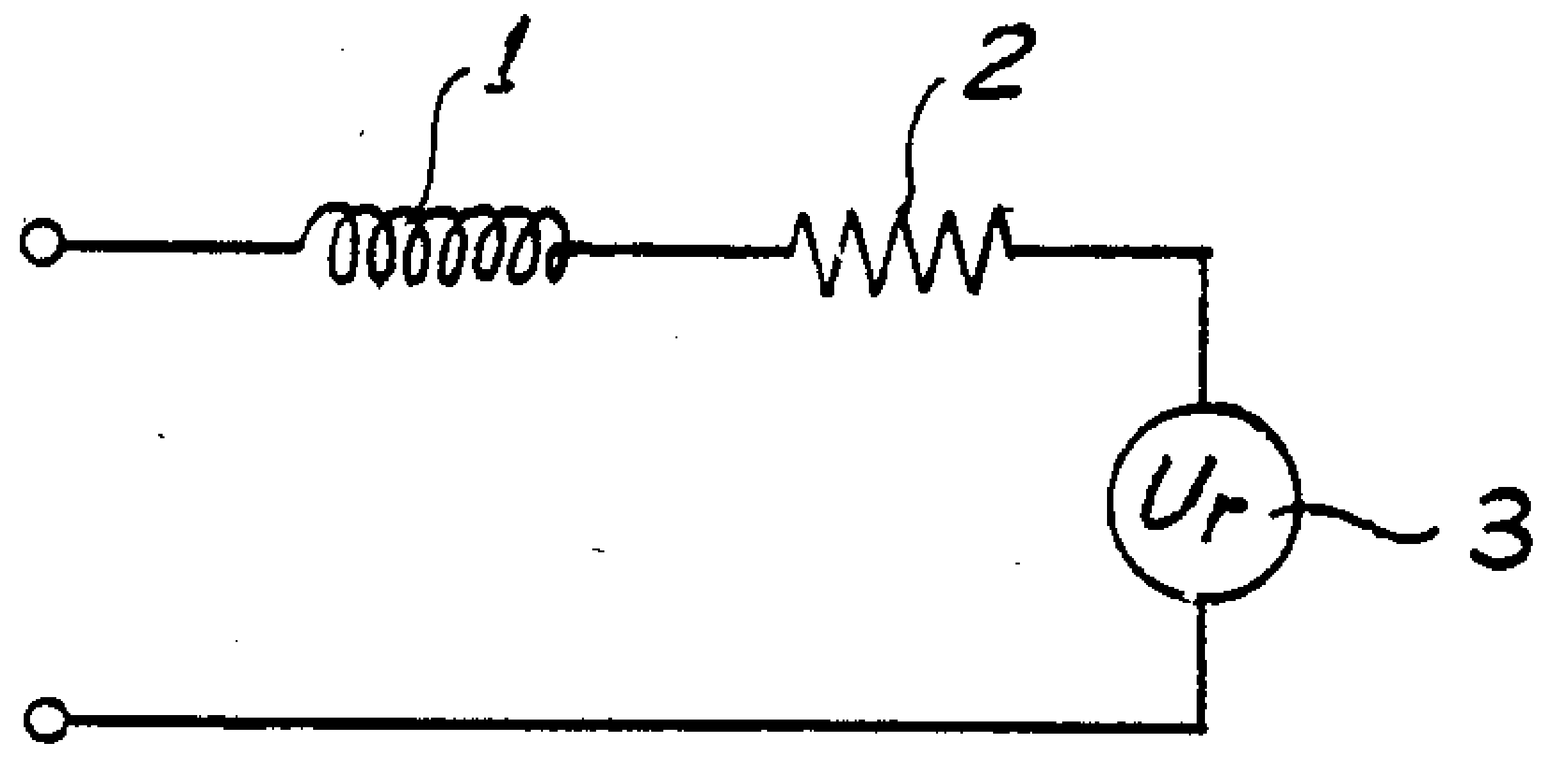


Fig. 1

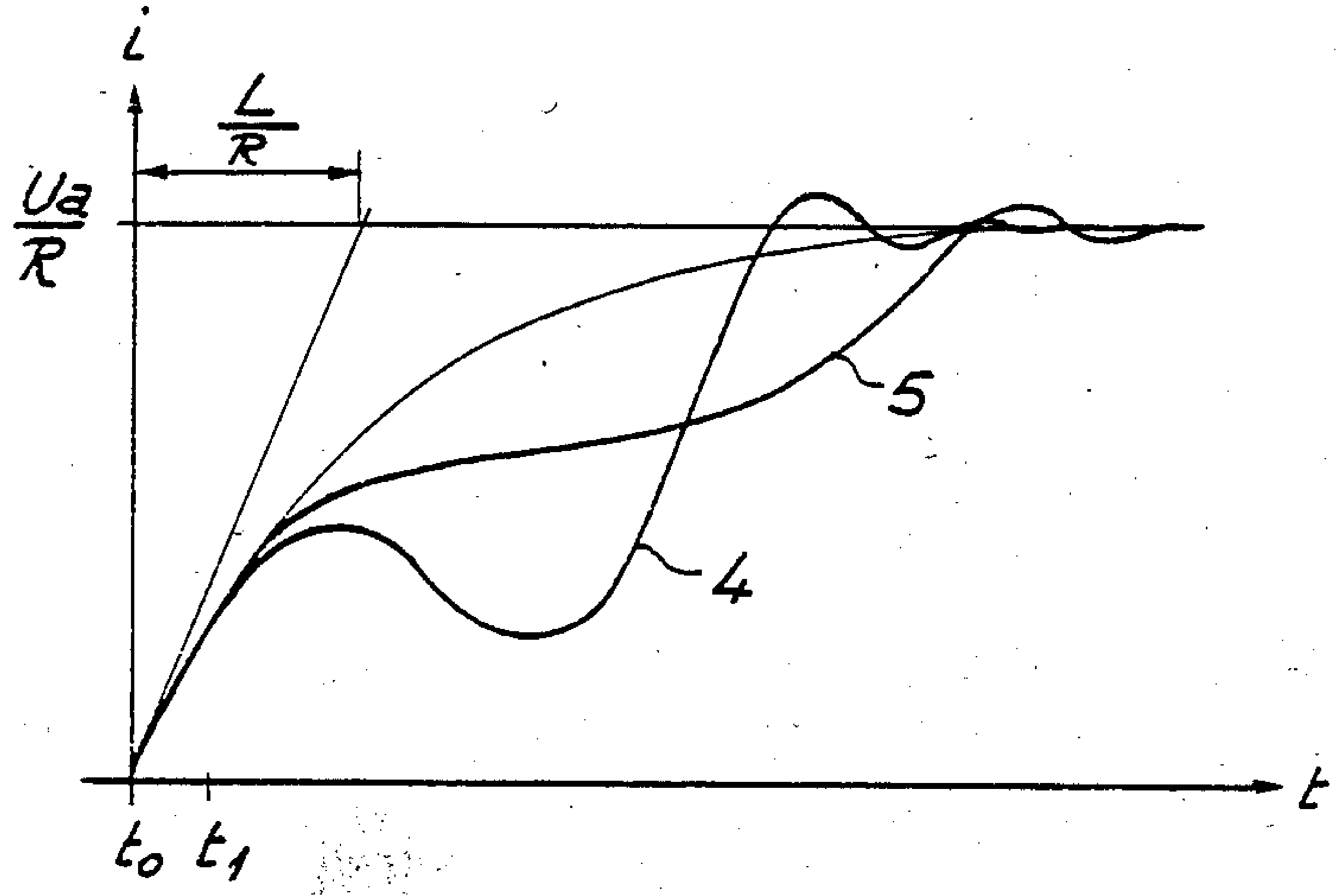


Fig. 2a

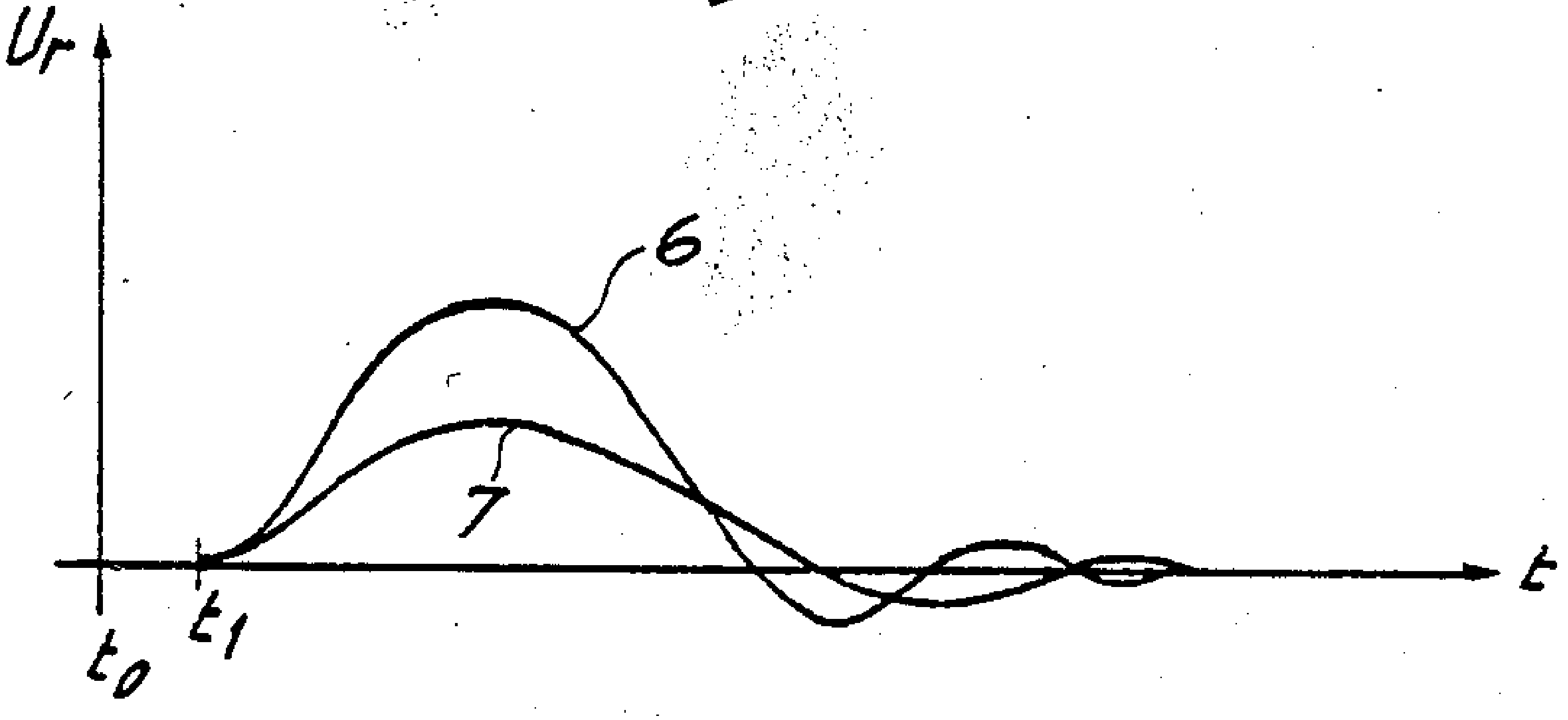


Fig. 2b

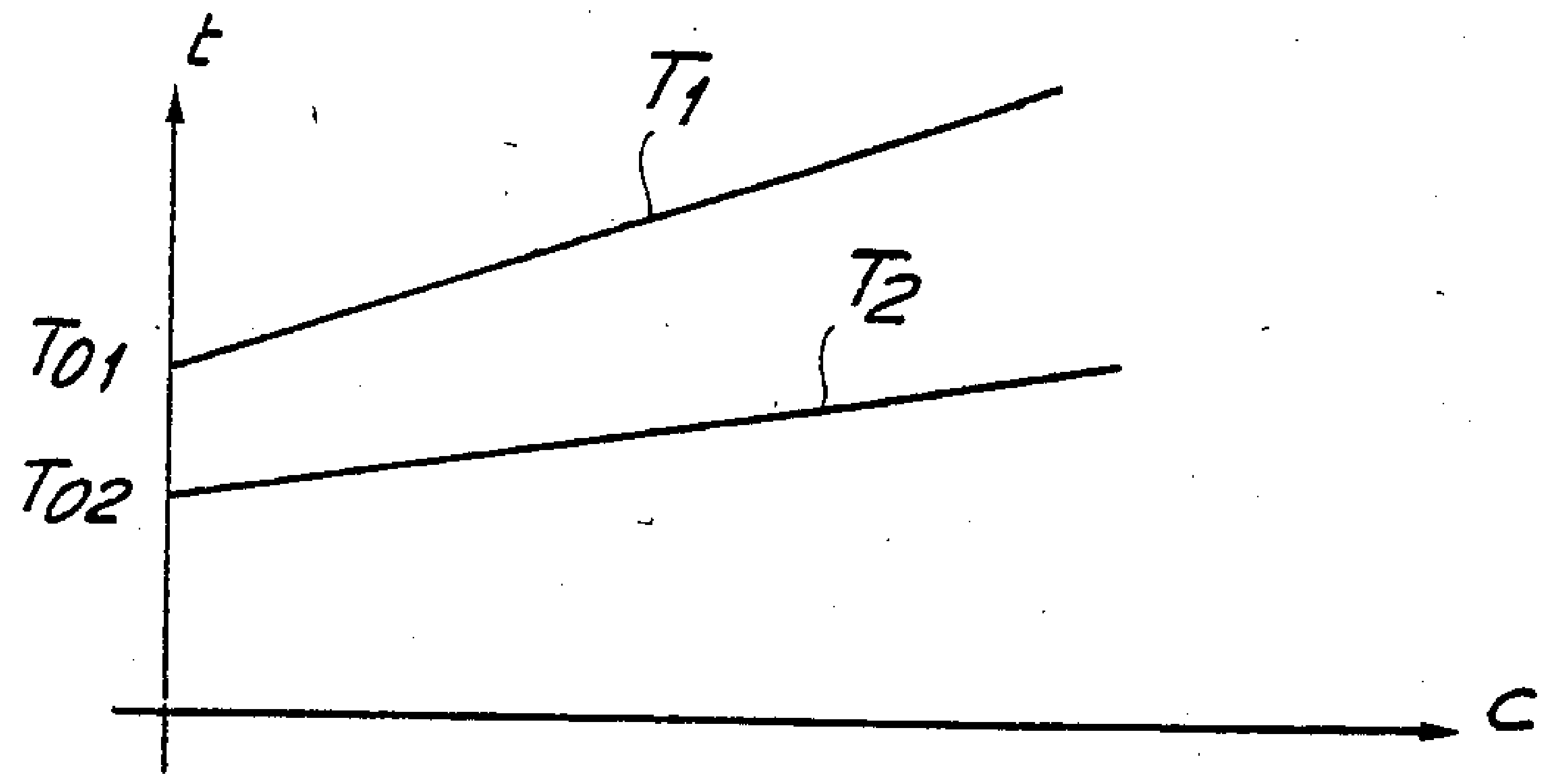


Fig. 3

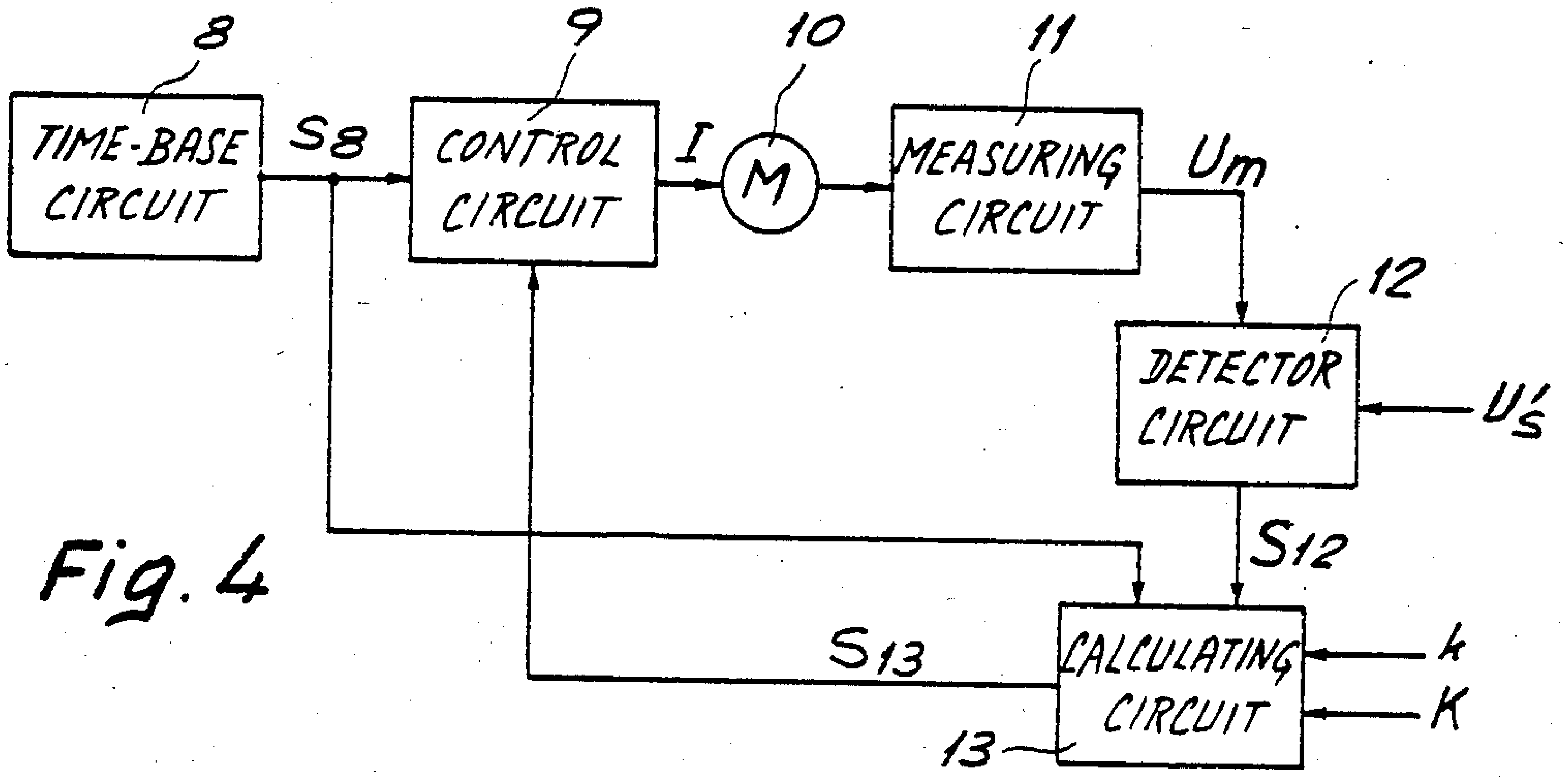


Fig. 4

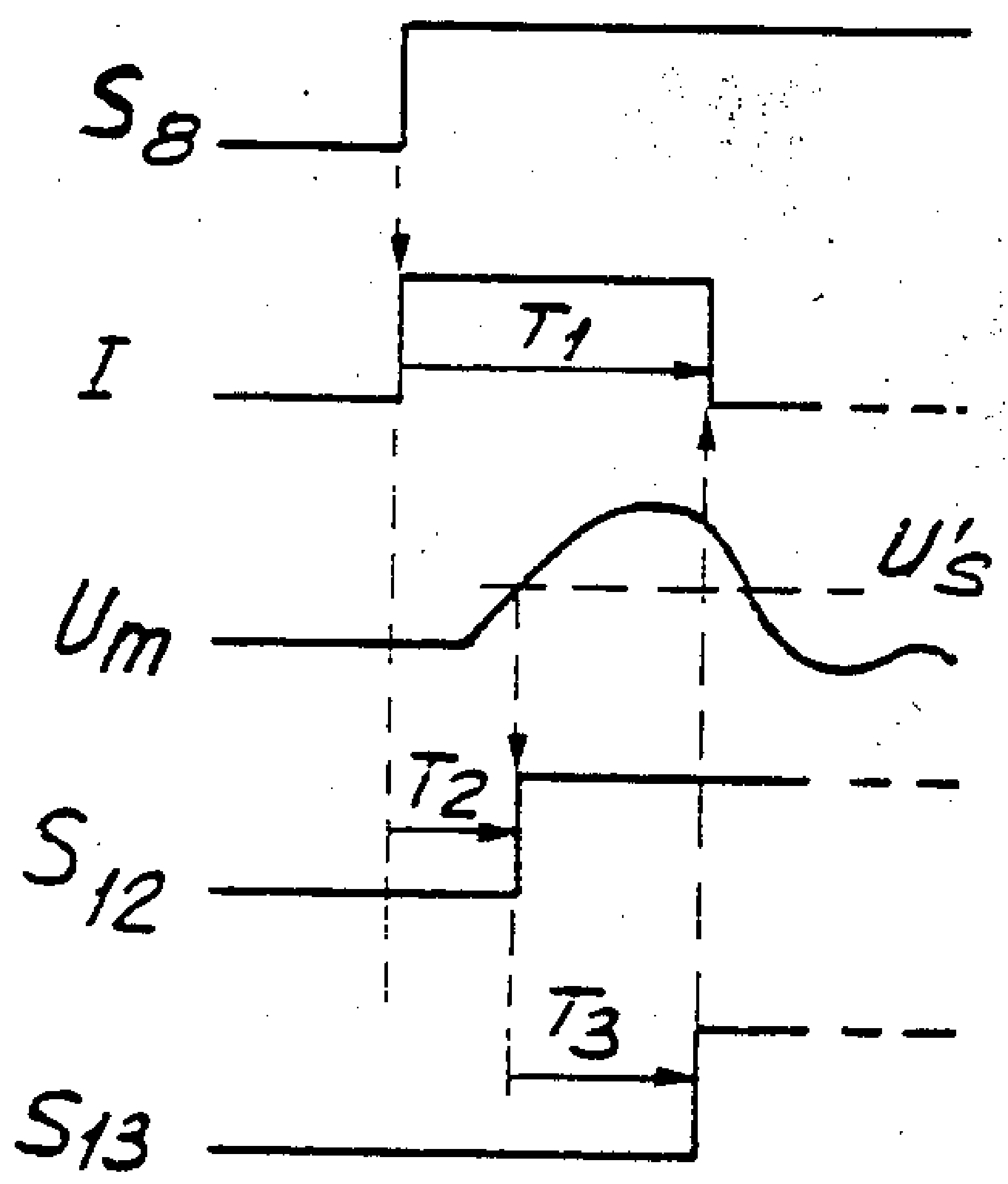


Fig. 5

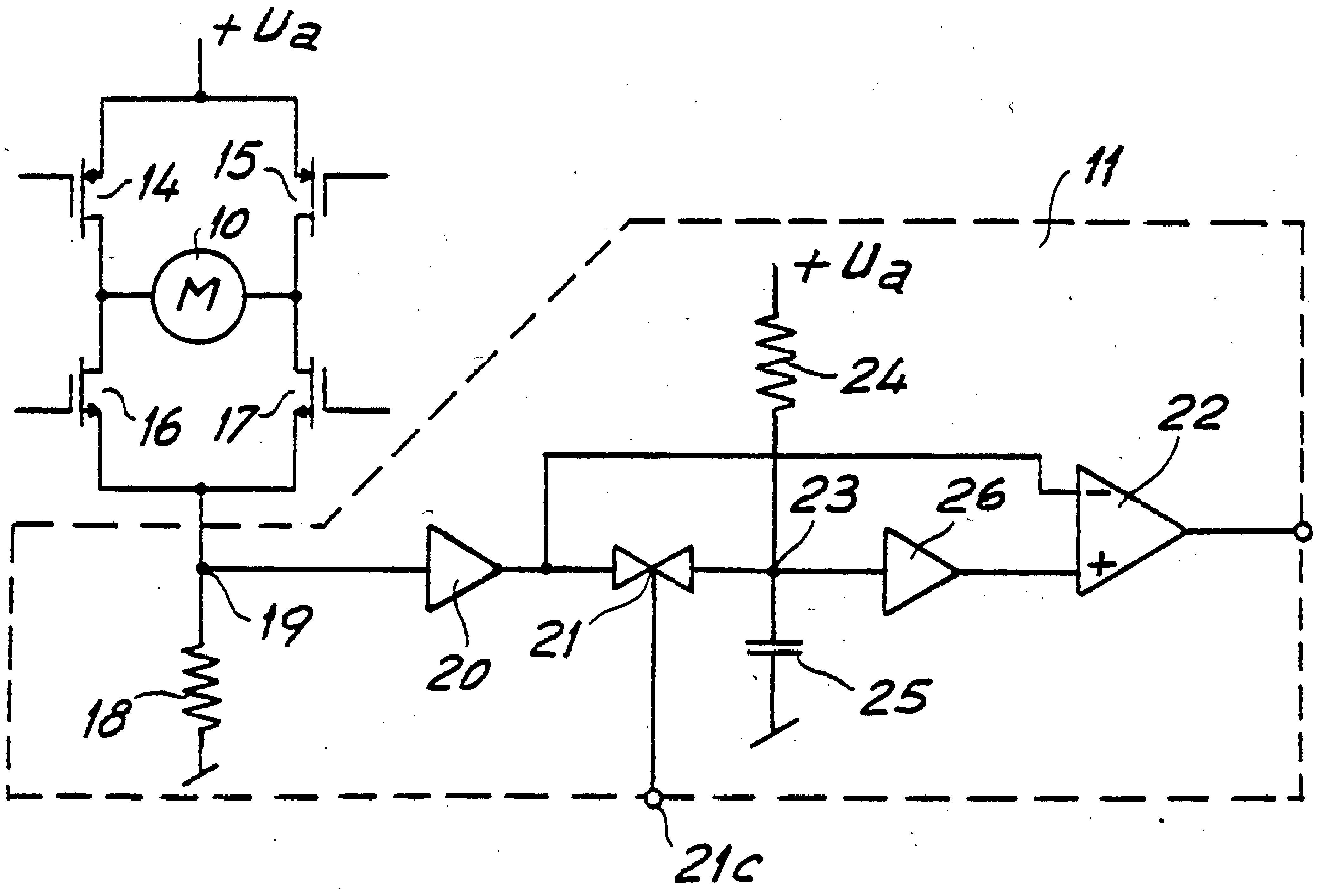

+Ua
14
15
10
M
16
17
11
+Ua
24
22
23
26
−
+
19
18
20
21
25
21c

Fig. 6

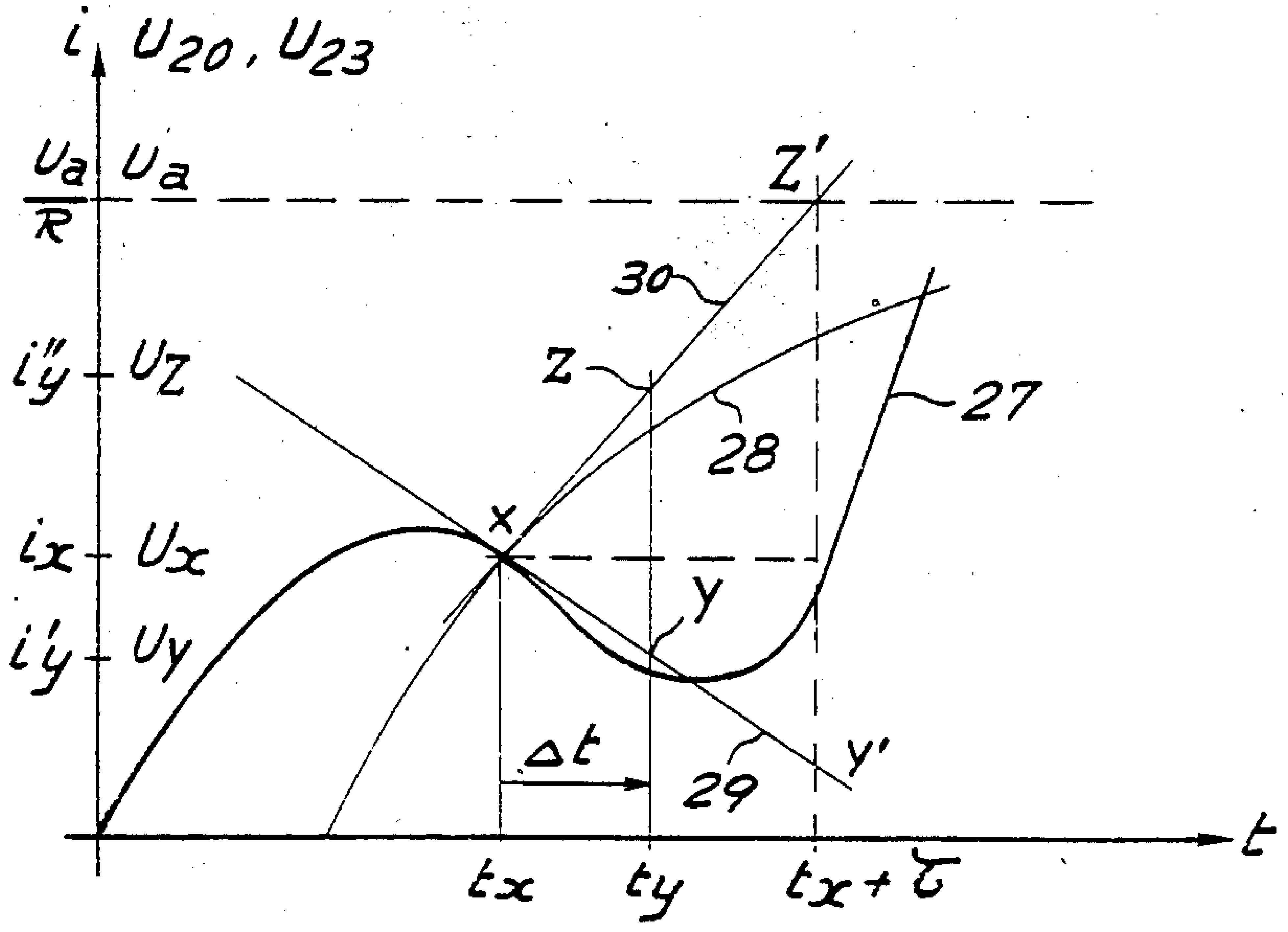

i
U20, U23
Ua/R
Ua
Z'
30
i''y
UZ
Z
28
27
ix
Ux
x
i'y
Uy
Y
Δt
29
Y'
t
tx
ty
tx + τ

Fig. 7

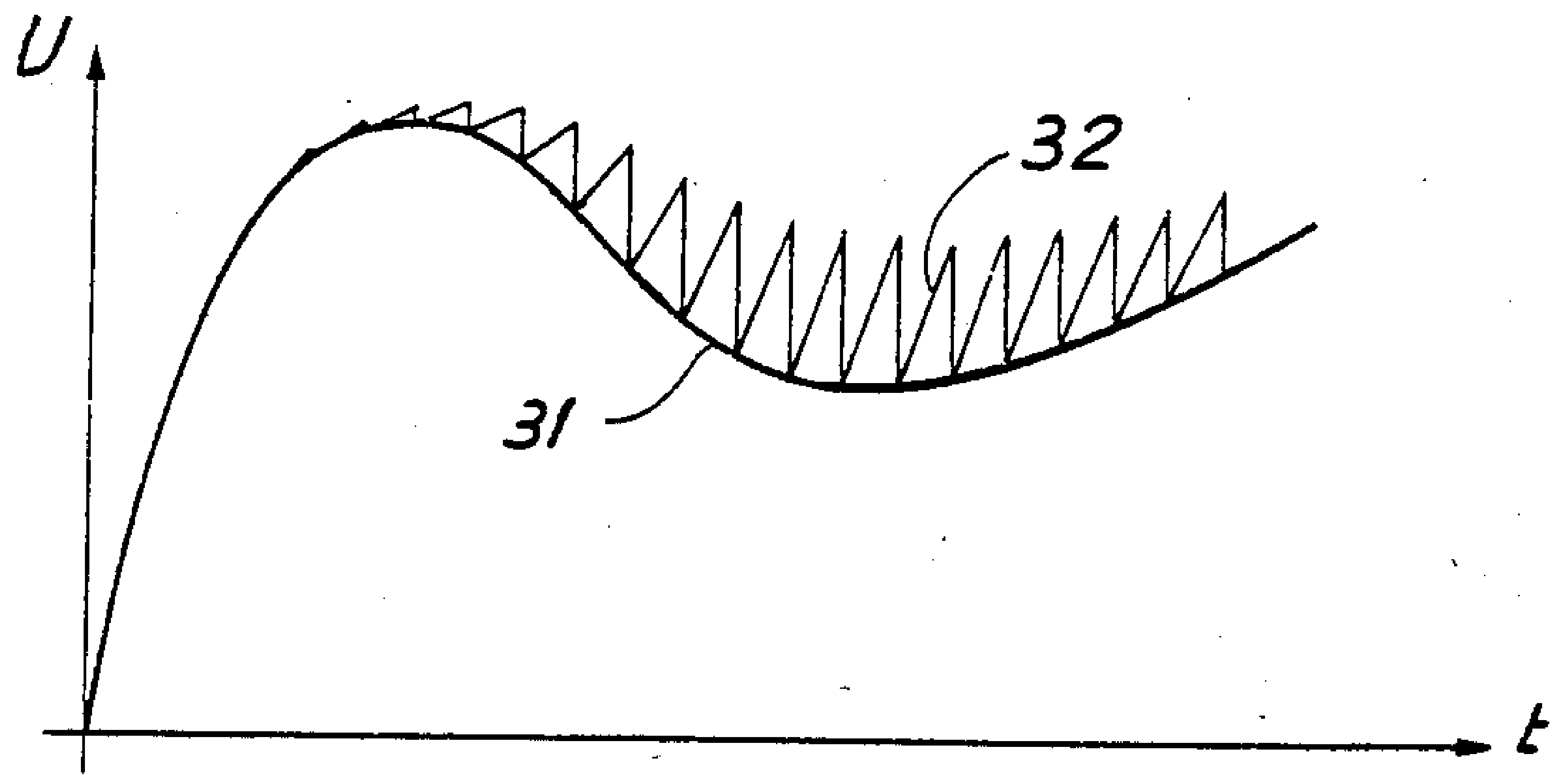


Fig.8a

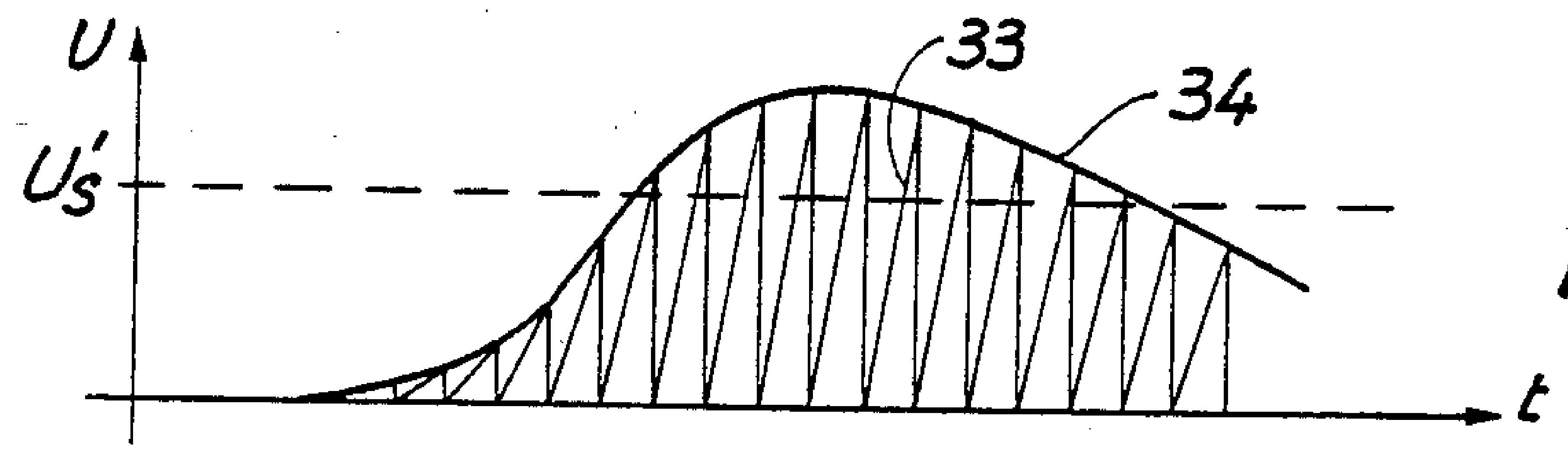


Fig.8b

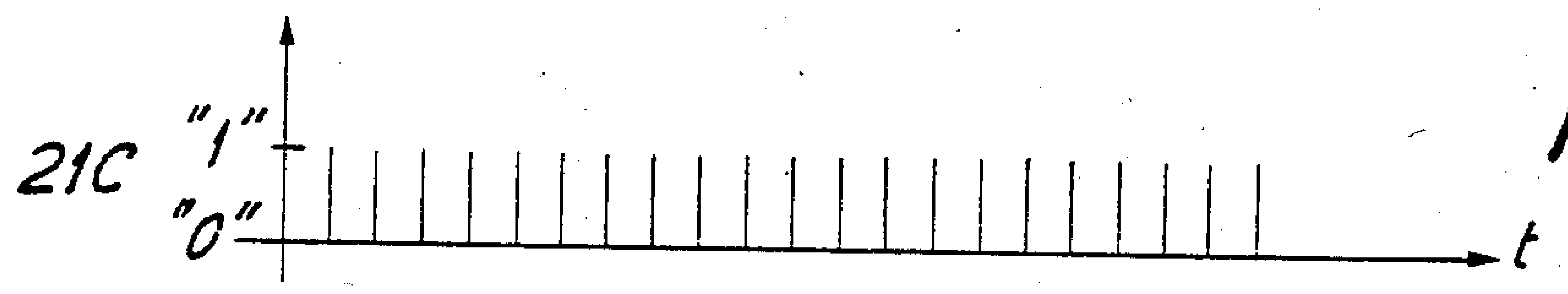


Fig. 8c

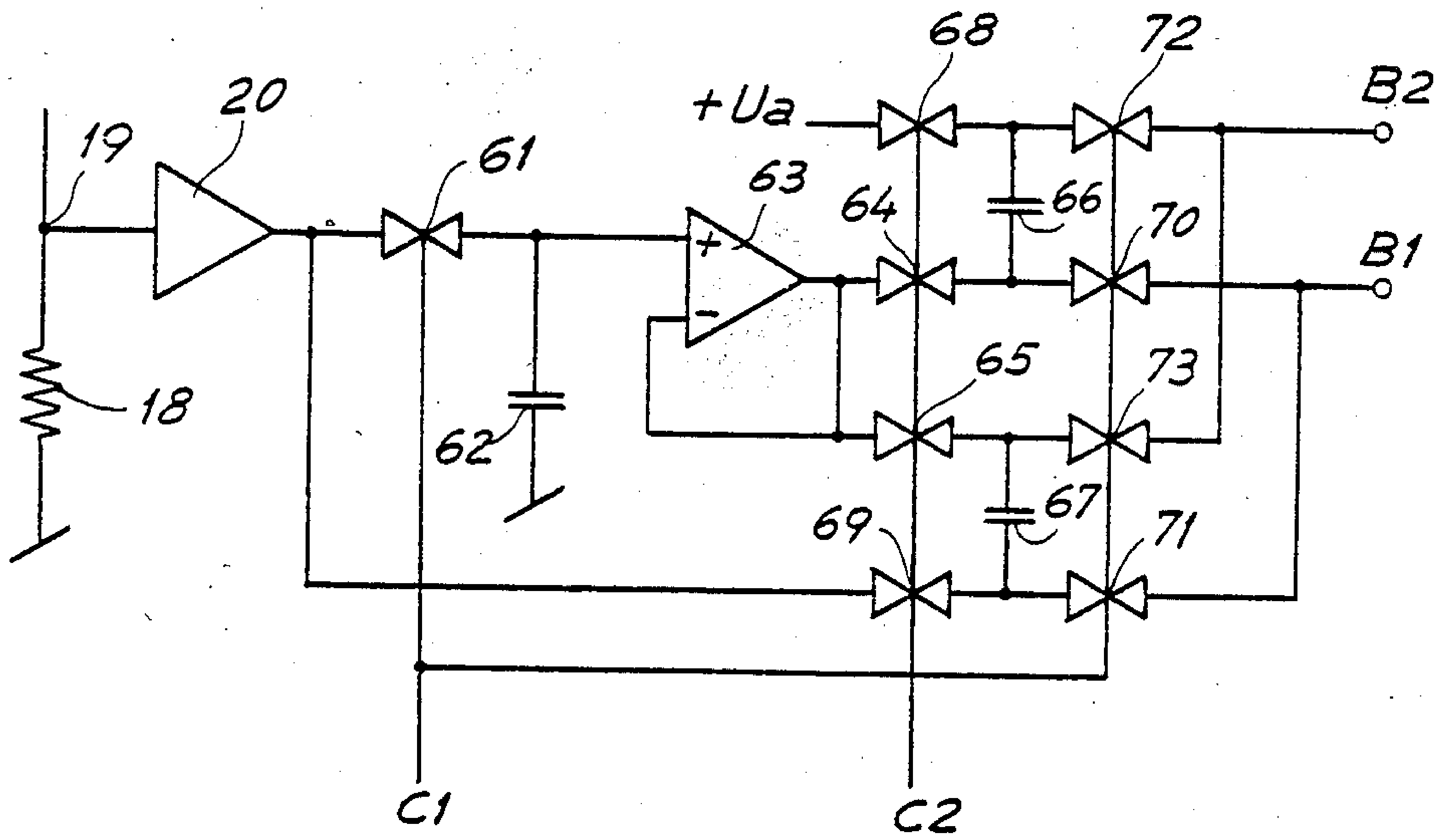


Fig.9

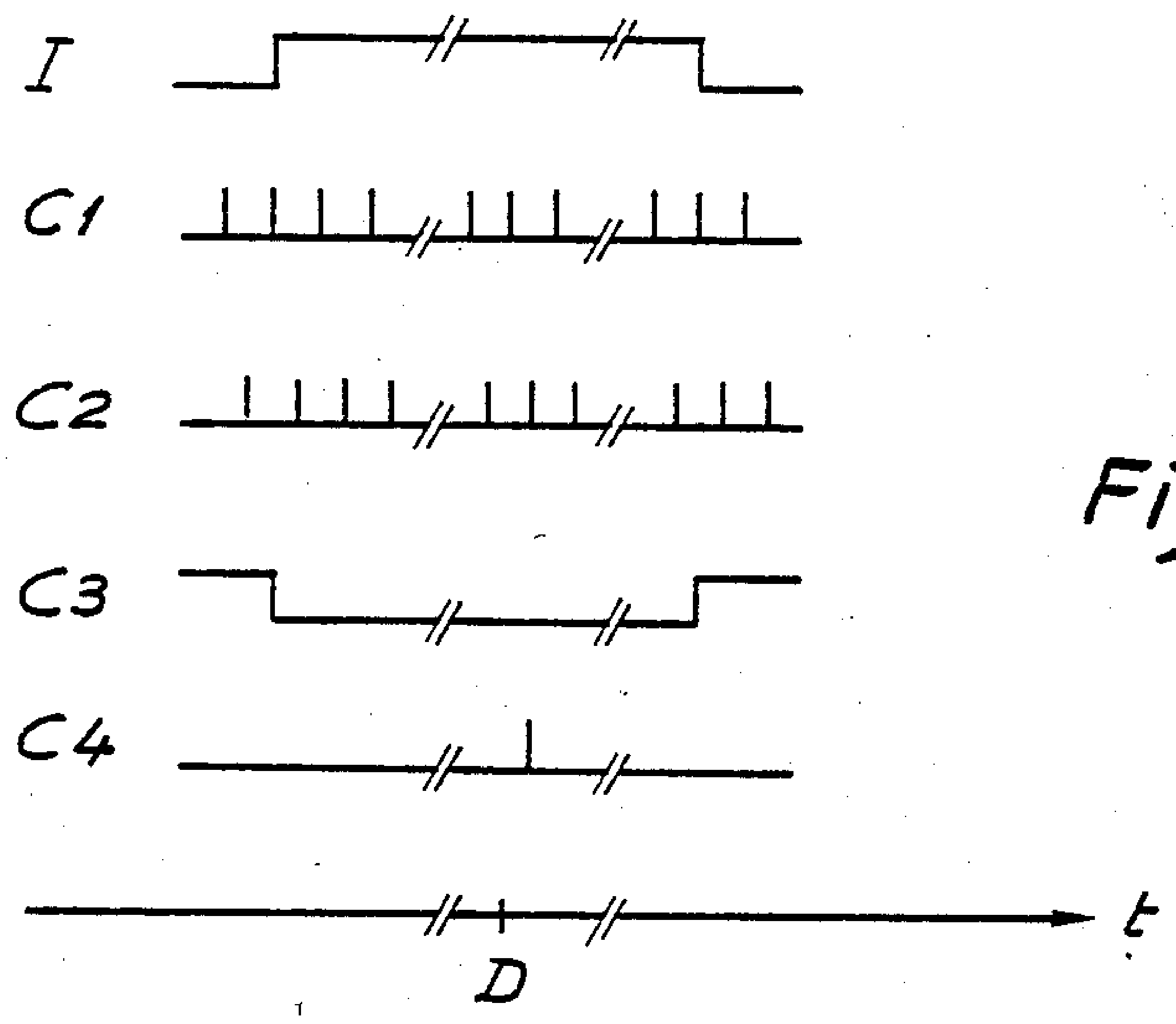

I
C1
C2
C3
C4
t
D

Fig. 10

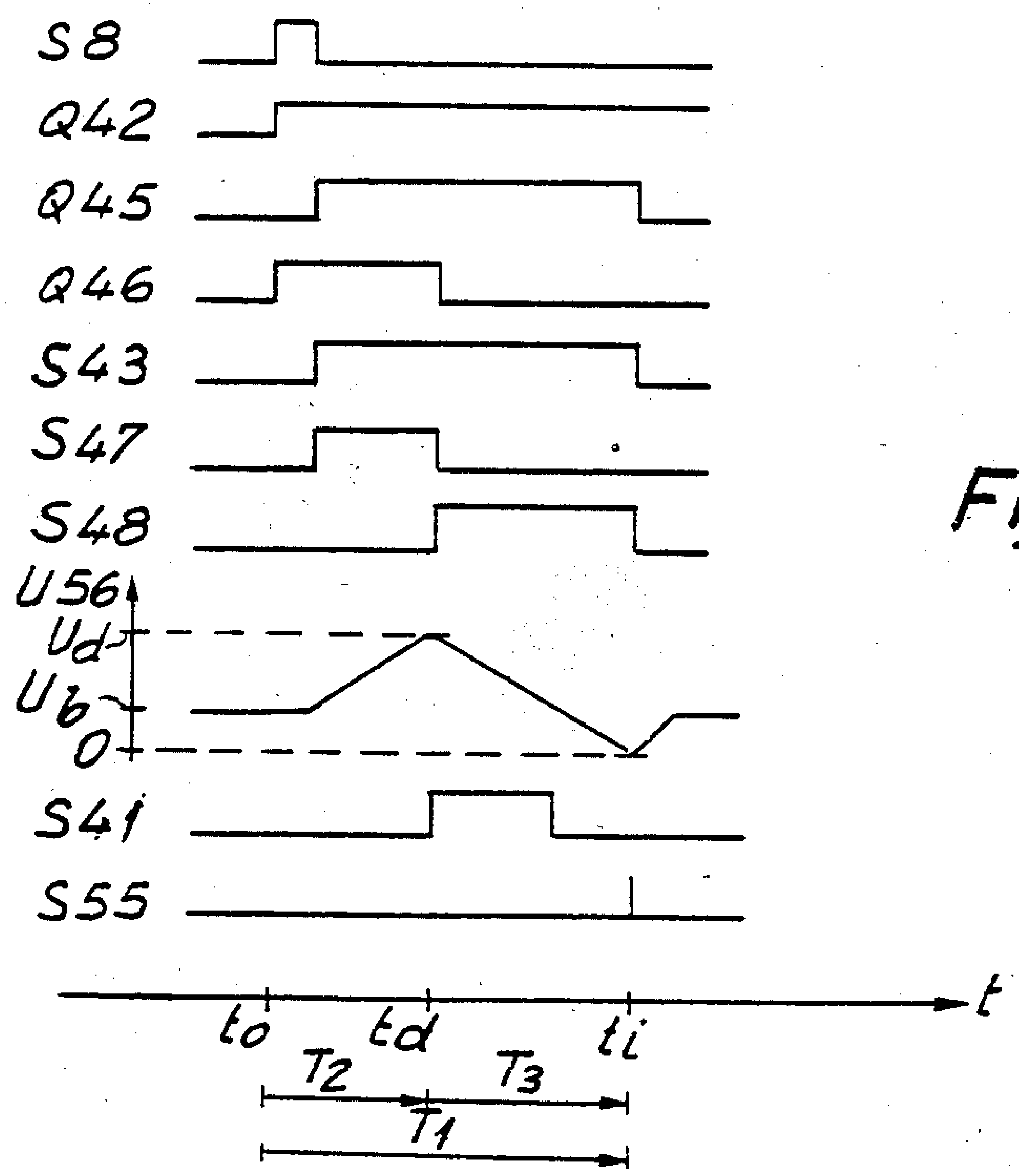
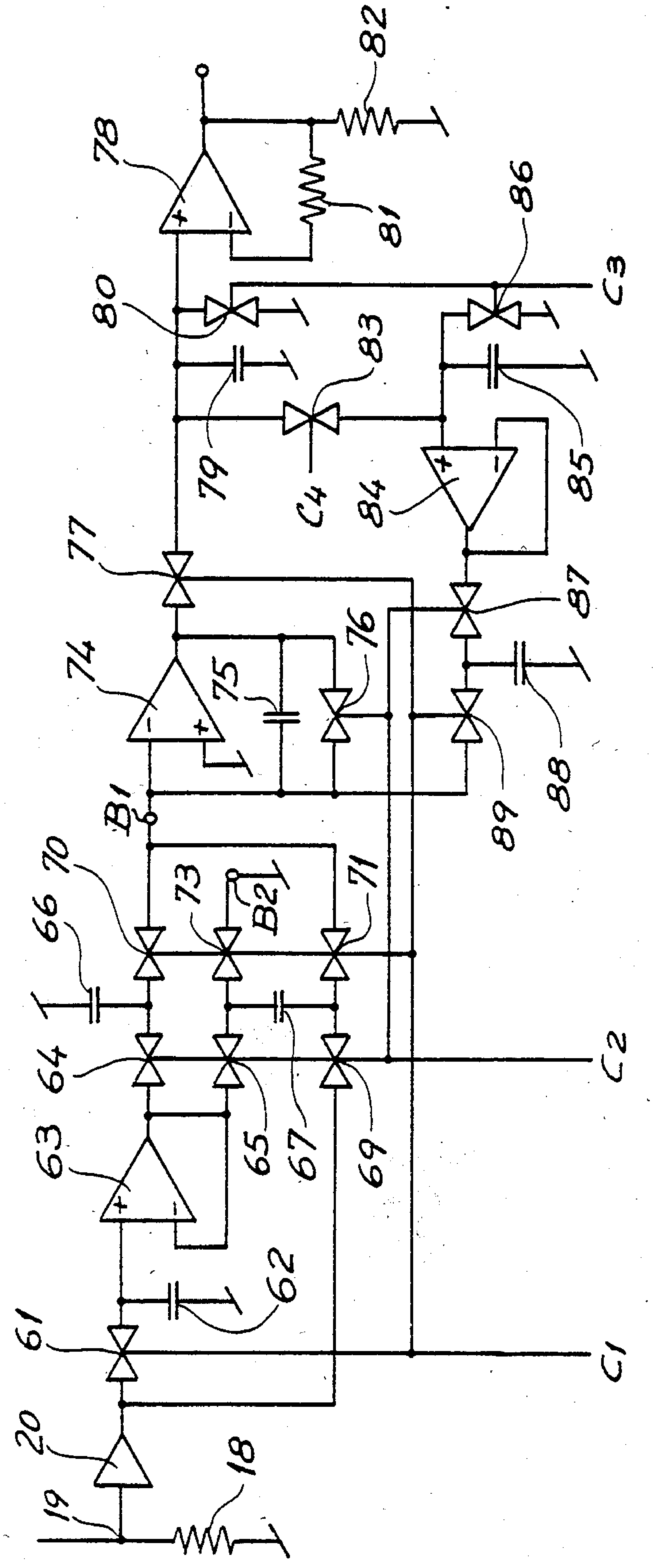

S8
Q42
Q45
Q46
S43
S47
S48
U56
Ud
Ub
0
S41
S55
t
to
td
ti
T2
T3
T1

Fig. 13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78
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C3
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C4
84
77
87
74
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76
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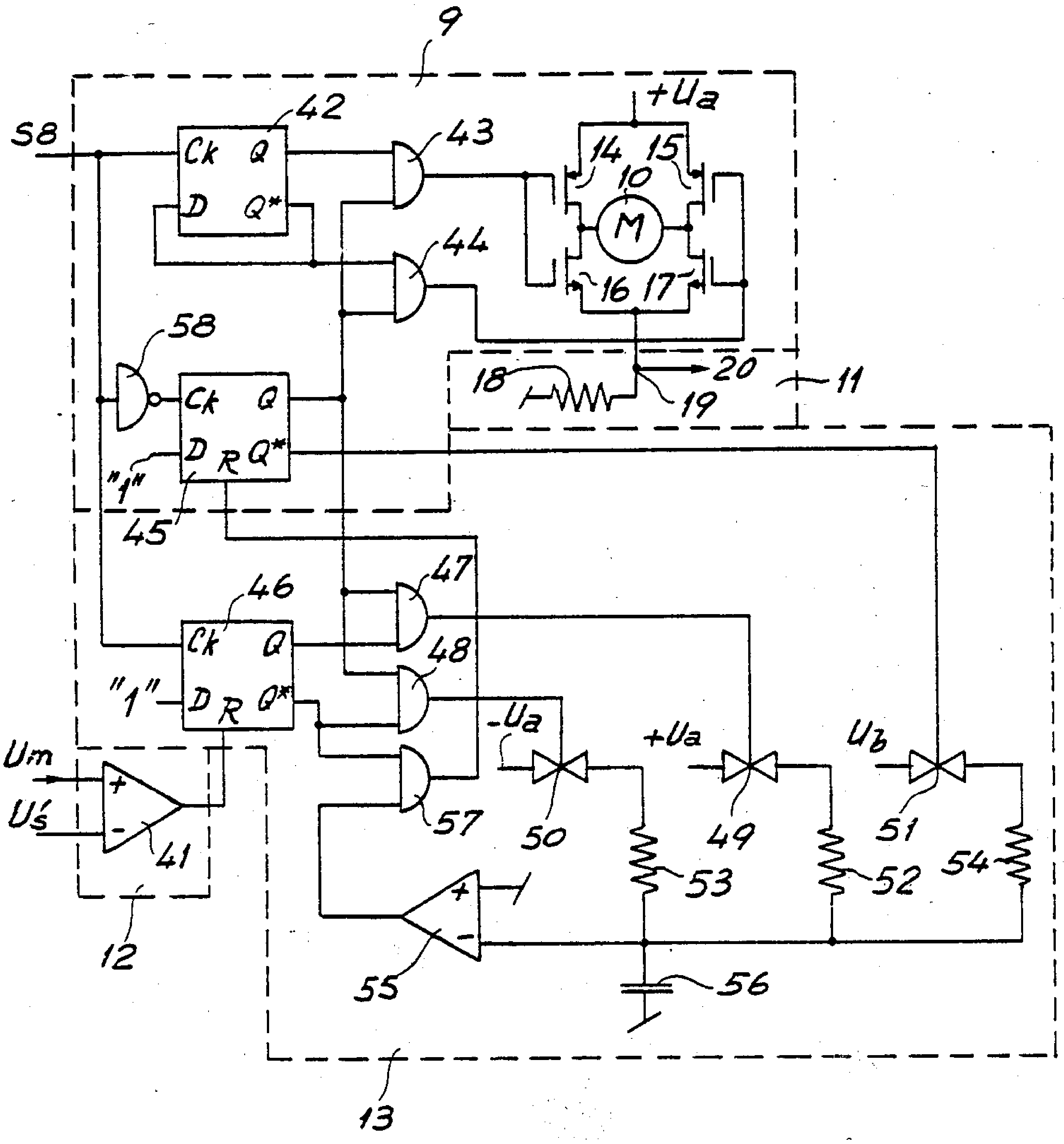
89
B1
70
66
73
B2
71
64
65
67
69
C2
63
62
61
C1
20
18
19

Fig. 11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S8
42
Ck Q
D Q*
43
+Ua
14 15
10
M
44
16 17
58
Ck Q
D R Q*
"1"
45
18
20
19
11
46
Ck Q
"1" D R Q*
47
48
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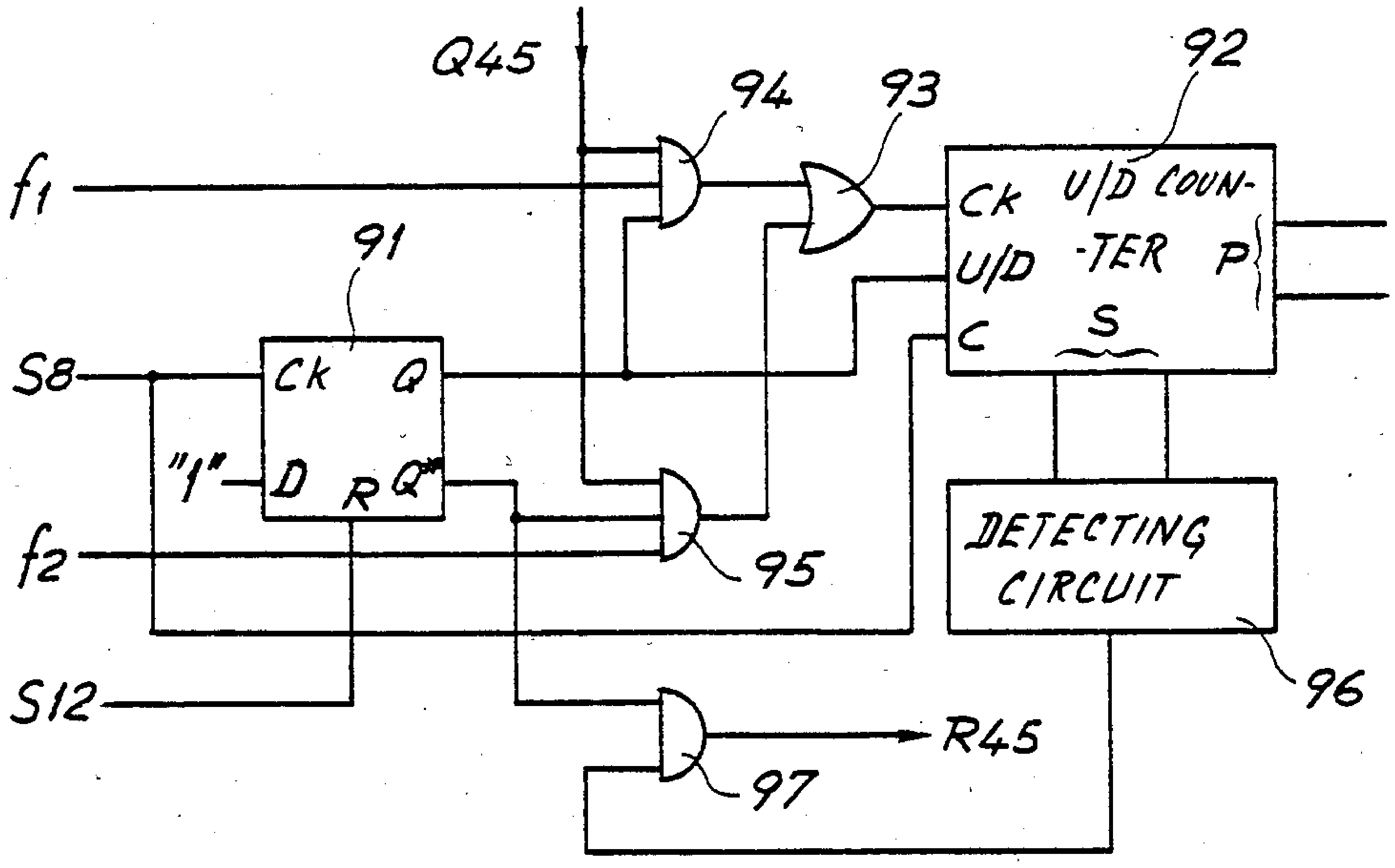
-Ua
+Ua
Ub
50
49
51
53
52
54
55
56
Um
Us
41
12
13

Fig. 12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f2
S12
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D
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Q
Q*
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R45
Ck
U/D
C
U/D COUN-TER
S
P
92
DETECTING CIRCUIT
96

Fig.14

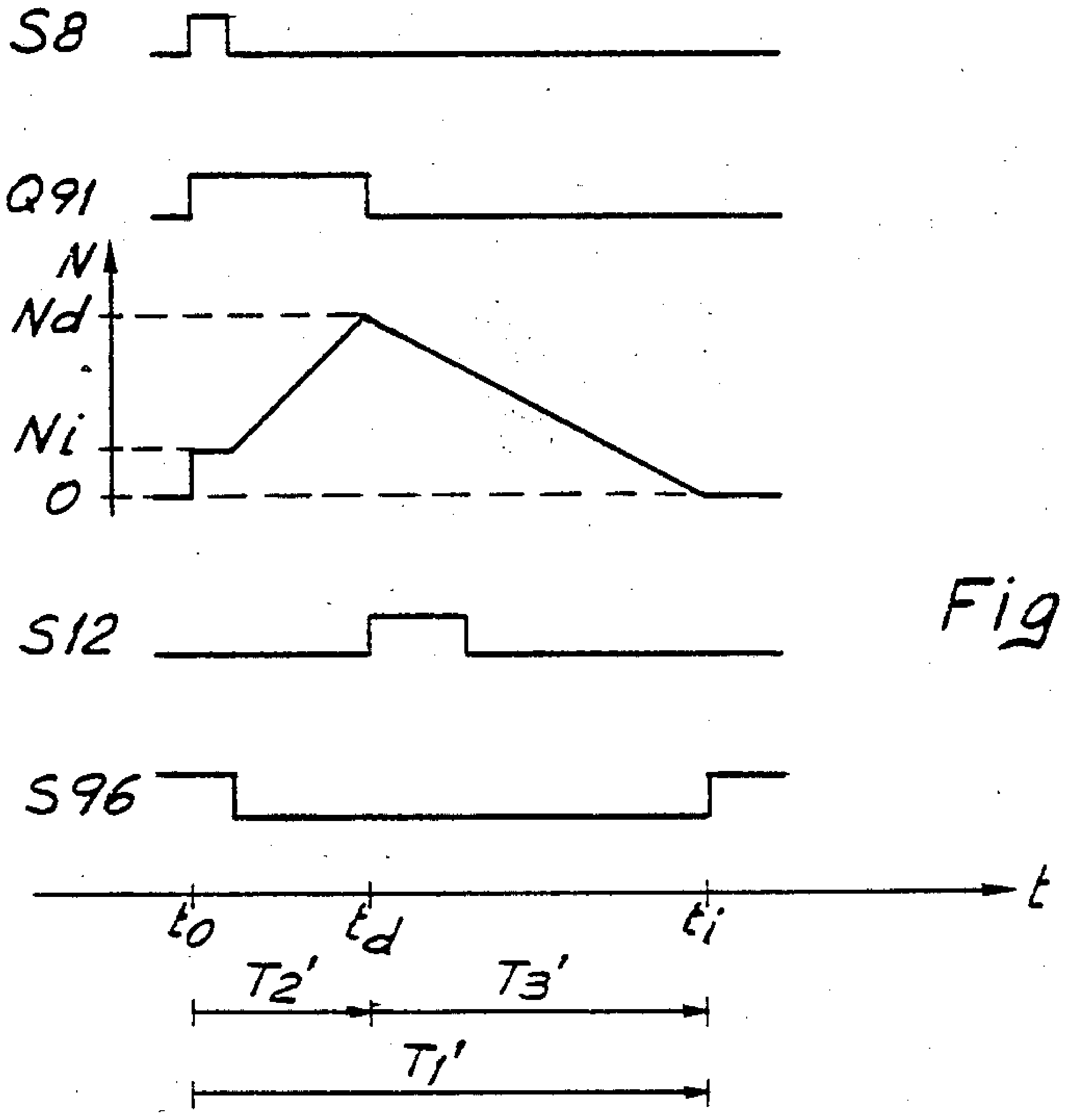
S8
Q91
N
Nd
Ni
0
S12
S96
t
t0
td
ti
T2'
T3'
T1'

Fig.15

METHOD FOR REDUCING THE CONSUMPTION OF A STEPPING MOTOR AND DEVICE FOR CARRYING OUT THE METHOD

This application is a continuation of Ser. No. 345,952, filed Feb. 4, 1982, and now U.S. Pat. No. 4,446,413.

BACKGROUND OF THE INVENTION

The present invention relates to a method for reducing the consumption of a stepping motor by automatically adapting the duration of each driving pulse supplied thereto to the load which is to be driven by the motor in response to said driving pulse.

The present invention also relates to a device for carrying out the method.

Stepping motors are used in many devices in which a mechanical member is to be moved by a given amount in response to an electrical signal. They are used in particular in electronic timepieces in which the time display hands must be moved by a given distance in response to pulses of a highly precise period, which are supplied by a time base.

In such timepieces, the major part of the power supplied by the electrical power source, which is generally a battery, is consumed by the stepping motor. As the space available in timepieces is greatly restricted, it is important for the level of consumption of the motor to be limited as far as possible, in order to increase the service life of the battery or, for a given service life, to be able to reduce the space occupied thereby.

In most of the present-day timepieces, the duration of the driving pulses which are supplied to the motor at regular intervals is constant. The duration of the driving pulses is so selected as to ensure proper operation of the motor even under the worst conditions, that is to say, with a low battery voltage, while driving the calendar mechanism, when subjected to shocks or in the presence of an external magnetic field, etc. As such poor conditions occur only rarely, the motor is over-powered in most cases.

It is possible to substantially reduce the power consumption of the motor by adapting the power supplied by the driving pulses to the instantaneous load to be driven by the motor and to the supply voltage.

One solution to this problem comprises providing a pulse shaping circuit capable of producing pulses of different durations and a device for detecting rotation or non-rotation of the motor. The duration of the driving pulses applied to the motor is progressively reduced until the device detects that a step has not been performed. A catch-up pulse is then applied to the motor and the energy of the normal driving pulses is fixed at a higher value which is maintained for a certain period of time. If the motor has rotated normally during that period, the duration of the pulses is again reduced. Such a design does not provide for the driving pulses to be permanently and rapidly adapted to the load on the motor. In addition, this slow adaptation procedure and the production of catch-up pulses when the motor does not perform a stepping movement mean that the power consumption is higher than necessary.

In order to overcome this disadvantage, it is known to provide devices which adapt the duration of each driving pulse to the load to be entrained by the motor in response to the driving pulse.

U.S. Pat. No. 3,500,103 describes a device for detecting the movement of the movable member of the motor by way of the voltage induced in a detection coil which is separate from the drive coil, and which interrupts the driving pulse when the movable member reaches either a given position or a given speed.

U.S. Pat.No. 3,855,781 proposes solutions according to which the position of the rotor is detected by measuring the voltage induced in an auxiliary coil or caused by the deformation of a piezoelectric element under the action of the teeth of one of the wheels of the wheel-train which is driven by the motor. That voltage is used to interrupt the driving pulse.

The device described in the two patents referred to above require additional elements for operation thereof, which makes them expensive and complicated to use.

French Pat. No. 2 200 675 proposes detecting the variation in current in the actuating coil of the motor and interrupting the driving pulse when the current passes through a minimum. The limits of this detection operation are imposed by the form of the current which depends on the time constant of the circuit, the counter-electromotive force induced, and the load on the motor. In some cases, the current minimum may disappear, which renders the control device inoperative.

In addition, U.S. Pat. No. 4,114,364 describes a circuit for controlling the duration of the driving pulses in dependence on the load on the motor, which comprises means for detecting the current in the actuating coil and means for interrupting the pulse when that current reaches a value equal to the ratio between the supply voltage of the coil and its d.c. resistance, that is to say, when the rotor has concluded its stepping motion. Also provided is the possibility of interrupting the pulse before the current has reached that value.

All the above-described devices use measurement of a physical parameter such as the speed or position of the rotor or such as the current flowing in the coil. The measurement made is used directly or by comparison with a reference value, to control interrupting the driving pulse. Now, none of the above-mentioned physical parameters gives an absolute indication as to the precise moment at which the driving pulse is to be interrupted in order for the power consumption of the motor really to be at a minimum. All these devices therefore cause the driving pulse to be interrupted at an arbitrarily selected moment which is generally not the optimum moment. In practice, these devices must take account of safety factors such that, most of the time, the motor consumes too much energy or does not operate safely.

SUMMARY OF THE INVENTION

This disadvantage is overcome by the method according to the invention which comprises the steps of measuring the voltage induced in the coil of the motor by the movement of the rotor, and interrupting the driving pulse in dependence on said measurement of the induced voltage.

The voltage induced in the coil by movement of the rotor is closely linked to the mechanical power produced by the motor, by the relationship:

$$\int U_r i \cdot dt = \int C \cdot w \cdot dt$$

which U_r in this induced voltage, i is the current flowing in the coil, C is the torque produced by the motor and w is the angular speed of the rotor.

The second term of the foregoing equation represents the total mechanical power produced by the motor during one of its steps, and the first term represents the electrical energy which is converted into the mechanical energy by the motor.

The above-indicated relationship shows that the voltage U_r induced in the coil by rotation of the rotor is directly linked to the mechanical power produced by the motor. The current i which is also involved in that relationship and all the other physical parameters which can be measured on a motor during its rotation also depend on factors which are not linked to the mechanical power mentioned above, such as the voltage of the power source and the ohmic resistance of the coil. This means that measuring the induced voltage U_r constitutes the most appropriate method for accurately and safely determining the optimum moment for interrupting the driving pulse.

It should be noted that the voltage induced in the coil by movement of the rotor is only a part of the total voltage induced, which is referred to in French Pat. No. 2 200 675 and the maximum of which coincides with the minimum of the current flowing in the coil, when that minimum exists. The other part of the total voltage induced is formed by the self-induction voltage generated in the coil by the variations in the current flowing therein.

As the above-mentioned self-induction voltage is not directly linked to the power supplied by the motor, the total voltage induced does not constitute a suitable parameter for determining the optimum moment for interrupting the driving pulse. Added to that is the above-mentioned fact that the current in the coil does not always have a minimum. In addition, when that minimum is present, it is not sufficiently clearly marked for it to be detected accurately.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in greater detail with reference to the accompanying drawing in which:

FIG. **1** shows the equivalent diagram of a stepping motor;

FIG. *2a* shows the variation in the current in the coil of the motor under two motor load situations;

FIG. *2b* shows the variation in the voltage induced in the coil by rotation of the rotor under the same load conditions;

FIG. **3** shows the variation in the duration of the minimum driving pulse and the time taken by the induced voltage to reach a given threshold, depending on the load driven by the motor;

FIG. **4** is a block circuit diagram of an embodiment of the device according to the invention;

FIG. **5** illustrates the mode of operation of the device of FIG. **4**;

FIG. **6** is a circuit diagram of a first embodiment of a circuit for measuring the voltage induced in the coil by rotation of the rotor;

FIG. **7** shows the principle of operation of the circuit of FIG. **6**;

FIGS. *8a–8c* show the mode of operation of the circuit of FIG. **6**;

FIG. **9** is a circuit diagram of a second embodiment of a circuit for measuring the voltage induced in the coil by rotation of the rotor;

FIG. **10** illustrates the mode of operation of the circuit of FIG. **9**;

FIG. **11** is a diagram of a third embodiment of a circuit for measuring the voltage induced in the coil by rotation of the rotor;

FIG. **12** is a diagram of a first embodiment of a circuit for using measurement of the voltage induced in the coil by rotation of the rotor to interrupt the driving pulse;

FIG. **13** illustrates the mode of operation of the circuit of FIG. **12**;

FIG. **14** is a diagram of a second embodiment of a circuit using measurement of the voltage induced in the coil by rotation of the rotor to interrupt the driving pulse; and

FIG. **15** illustrates the mode of operation of the circuit of FIG. **14**.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** shows the equivalent diagram of a stepping motor. The coil of the motor is represented by a coil **1** with an inductance L and a resistance of zero, and a resistor **2** whose resistance R is equal to the resistance of the motor coil. The source of voltage induced in the coil by rotation of the rotor is diagrammatically indicated by a voltage source **3**. The value of the induced voltage is designated U_r.

Curves **4** and **5** in FIG. *2a,* which are well known, illustrate the variation in the current i in the coil of the motor in dependence on time during the driving pulse in situations where the load driven by the motor is low and high respectively.

Curves **6** and **7** in FIG. *2b* illustrate, under the same load conditions, the variation in the voltage U_r as measured by a device which will be described hereinafter.

Curves **4** and **5** show that, just after the moment **T0** at which the driving pulse is initiated, the current in the coil increases in accordance with an exponential law, with a time constant equal to L/R, irrespective of the load to be driven by the motor. The rotor is still stationary and the voltage U_r is zero (FIG. *2b*).

The rotor begins to rotate at moment **t1**. The source **3** begins to supply the voltage U_r induced by rotation of the rotor, and the current i in the coil therefore ceases to be subject to an exponential variation. It follows a curve which depends on the load driven by the motor, curves **4** and **5** being two examples thereof. The voltage U_r follows a curve which also depends on the load driven by the motor. Curve **6** in FIG. *2b* corresponds to curve **4** in FIG. *2a* while curve **7** corresponds to curve **5**.

Irrespective of the load driven by the motor, the voltage U_r passes through a maximum before passing through zero at the moment at which the rotor passes through the position that is would finally assume after a few oscillations, if the driving pulse would not be interrupted.

The voltage U_r then oscillates about zero until the rotor stops.

There are several possible ways of making use of the information supplied by measuring the voltage U_r. Like the other physical parameters which can be measured on the motor, that voltage U_r does not have a particular point which coincides precisely with the moment at which the driving pulse is to be interrupted in order to have minimum motor consumption.

However, measurements have shown that, irrespective of the kind of information which is extracted from the measurement of that voltage U_r, that information is very directly linked to the optimum duration of the driving pulse. The law linking that information and that duration is always a simple law which permits the information extracted from measurement of the voltage U_r to be easily put to use.

Among the information which can be extracted from measurement of the voltage U_r, mention may be made of the position in time or of the amplitude of the maximum of the above-mentioned voltage U_r, the time taken by that voltage to reach a certain threshold on its rising edge or its falling edge, the derivative or the integral thereof, etc. Tests have shown that the information given by the time taken by the voltage U_r to reach a certain threshold is easier to extract from measurement of the voltage U_r and to put to use for determining the optimum duration of the driving pulse.

FIG. **3** illustrates the variation in the minimum duration **T1** of the driving pulse required to rotate a motor in dependence on the torque C that the motor is to produce. That variation is substantially linear and has a fairly low degree of dispersion for a given type of motor. It can be expressed by the following relationship:

$$T1 = T01 + a \cdot C$$

in which **T01** is the minimum duration of the driving pulse for a zero load and a is the slope of the straight line.

The variation in the time T2 taken by the voltage U_r to reach a given threshold U_s is also shown in FIG. **3**. It is also substantially linear and may be expressed by the following relationship:

$$T2 = T02 + b \cdot C$$

in which **T02** is the time taken by the voltage U_r to reach the threshold voltage U_s in the absence of load and b is the slope of the straight line.

It is interesting to note that, in a fairly wide range of values in respect of the threshold voltage U_s, the relationship between T2 and C remains linear. The terms T02 and b obviously depend on the threshold voltage U_s selected.

The relationship between the times T1 and T2 is also linear and is given by the equation:

$$T1 = \frac{a}{b}\left(T2 - T02 + \frac{b}{a}\,T01\right)$$

In that equation, the terms a, b, **T01** and **T02** are constants for a given type of motor and for a given threshold voltage U_s. It can therefore be written as follows:

$$T1 = k(T2 + K) \tag{1}$$

with

$$k = (a/b) \text{ and } K = (b/a)T01 - T02$$

The terms k and K can be easily calculated from measuring the times **T01** and **T02** and the times T1 and T2 for a known load. Once they have been determined, for a particular type of motor, they can be used in the circuit for controlling that type of motor. FIG. **4** shows the basic circuit diagram of such a circuit. FIG. **5** shows the variation in the signal at some points in FIG. **4**.

In FIG. **4**, reference numeral **8** denotes a circuit the output of which supplies a signal **S8** to a control circuit **9** each time when the motor **10** is to advance by one step.

By way of non-limiting example, the circuit **8** may comprise the oscillator and the frequency divider chain of an electronic watch, and it can be so arranged as to supply other periodic signals at various frequencies. Those signals will be described hereinafter.

In response to the signal **S8**, the control circuit **9** supplies the driving pulse I to the motor **10**. When the motor **10** is a stepping motor such as is generally used in watches, correct polarity of the driving pulse I is also determined by the circuit **9**.

A measuring circuit **11** is connected to the motor **10**. It is so arranged, in a manner in respect of which examples will be set out hereinafter, as to supply a voltage U_m proportional to the voltage U_r induced in the coil of the motor by rotation of the rotor.

The measured voltage U_m is applied to a detector circuit **12** which supplies a signal **S12** at the moment that the voltage U_m exceeds a suitably selected reference voltage U_s'.

A calculating circuit **13**, embodiments of which will be described by way of example hereinafter, supplies a signal **S13** a certain time after having received the signal **S12**. The moment at which the signal **S13** is supplied depends on the time which has elasped between the beginning of the driving pulse and the advent of the signal **S12**, and on the value of the two constants k and K which are also supplied in a suitable form to the calculating circuit **13**. The signal **S13** is used by the control circuit **9** to interrupt the drive pulse I.

FIG. **6** shows the basic diagram of an example of the circuit **11** for measuring the voltage U_r. Like the other circuits which will be described hereinafter, the circuit **11** is supplied by a voltage source (not shown). The voltage source supplies a positive voltage $+U_a$ and a negative voltage $-U_a$ with respect to a middle point which is connected to the ground of the circuit. The voltage $-U_a$ is intended in particular to feed the differential amplifiers used in those circuits.

FIG. **6** shows the motor **10** connected in conventional manner in a bridge circuit comprising four MOS transistors **14,15,16** and **17**, forming part of the control circuit **9** in FIG. **4**. The transistors **14** and **15** which are of p type have their sources connected to the positive terminal $+U_a$ of the power source (not shown). The transistors **16** and **17** which are of n type have their source connected to the ground of the circuit, by way of a low-resistance measuring resistor **18** forming part of the measuring circuit **11** in FIG. **4**. The drains of the transistors **14** and **16** are connected to one of the terminals of the motor **10** and the drains of the transistors **15** and **17** to the other.

The gates of the four transistors **14** to **17** are connected to a logic circuit (not shown in FIG. **6**) which produces the logic signals required for controlling those transistors. An example of the logic circuit will be described below.

The measuring circuit **11** comprises an amplifier **20**, the input of which is connected to the point **19** which is common to the sources of the transistors **16** and **17** and to the resistor **18**. The gain of the amplifier **20** is so selected that its output voltage **U20** is equal to the supply voltage $+U_a$ when the current i flowing in the motor coil is equal to U_a/R.

The output of the amplifier **20** is connected to the input of a transmission gate **21** and to the inverting input of a differential amplifier **22**. The gate **21** is controlled by a logic signal **21C** which is produced for example by the circuit **8** in FIG. **4** and which will be described hereinafter.

The output of the gate **21** is connected to the junction point **23** of a resistor **24** having a value R24 and a capacitor **25** having a capacitance C25. The point **23** is also connected by way of an amplifier **26** to the non-inverting input of the differential amplifier **22**.

The sole purpose of the amplifier **26** is to avoid loading the R-C circuit **24–25** by the input of the amplifier **22**. The gain of the amplifier **26** is one.

The circuit formed by the resistor **24** and the capacitor **25** is connected between the terminal $+U_a$ of the power supply source and ground. The value R24 of the resistor **24** and the capacitance C25 of the capacitor **25** are so selected that:

$$R24 \cdot C25 = (L/R)$$

in which L and R are the inductance and the resistance of the motor coil, as referred to above.

When the signal **21C** is at logic state "0", the gate **21** is non-conducting. The voltage at the point **23** therefore varies exponentially towards its asymptotic value which is equal to the supply voltage $+U_a$, with the same time constant $\tau = R24 \cdot C25$ as the current which would flow in the coil of the motor if the rotor were blocked, that is to say, if the voltage U_r were zero.

When the signal **21C** is at logic state "1", the gate **21** is conducting and the voltage at point **23** is equal to the output voltage of the amplifier **20**.

FIG. **7** shows the principle of operation of that circuit. In FIG. **7**, curve **27** represents the variation in the output voltage **U20** of the amplifier **20**, during a driving pulse. The curve **27** is therefore an image of the current i flowing in the coil of the motor **10** during a driving pulse.

As long as the gate **21** is conducting the voltage U23 at point **23** follows the same curve **27**. The output voltage U22 of the differential amplifier **22** therefore remains at zero. If, at any moment t_x, the gate **21** becomes non-conducting, the voltage **U20** continues to follow the curve **27**. On the other hand, the voltage U23 begins to follow the curve **28** which is the exponential curve passing through point X, with a time constant $\tau = R24 \cdot C25$ and an asymptotic value equal to +Ua. The curve **28** is precisely the same as that which would be followed by the voltage U20 if, at moment t_x, the rotor were abruptly stopped, which would make the voltage U_r equal to zero. It is therefore an image of the current i′ which, under those conditions, would flow in the coil of the motor.

As the voltage U20 and U23 are applied to the inverting and direct inputs of the differential amplifier **22**, the output voltage U22 of the amplifier is therefore U23 −U20.

It will be shown hereinafter that, during a short moment after the gate **21** has become non-conducting, the voltage $U22 = U23 - U20$ is proportional to the voltage U_{rx}, that is to say, to the value of the voltage induced in the coil of the motor by rotation of the rotor at the moment t_x.

The voltage U20 is proportional to the current i flowing in the coil during a driving pulse. Generally, that current i can be expressed by the following relationship:

$$i(t) = \frac{U_a - U_r - L\frac{di}{dt}}{R} \qquad (2)$$

which is readily deduced from the circuit shown in FIG. **1** when the voltage $+U_a$ is applied to the motor by its control circuit (not shown in FIG. **1**).

At each point on the curve **27**, the slope thereof is given by the following equation which is readily deduced from equation (2):

$$\frac{di}{dt} = \frac{U_a - U_r - R \cdot i}{L}$$

At point X, the slope is given by:

$$\left.\frac{di}{dt}\right|_{t = t_x} = \frac{U_a - U_{rx} - R \cdot i_x}{L}$$

in which U_{rx} and i_x are respectively the values of U_r and i at point X.

The tangent **29** to the curve **27** at the point X therefore has the following equation:

$$i'(t) = \frac{U_a - U_{rx} - R \cdot i_x}{L} \cdot t + C1 \qquad (3)$$

in which C1 is an integration constant which can be calculated, taking account of the following condition:

$$i' = i_x \text{ for } t = t_x$$

With all calculations performed, the equation of the tangent **29** becomes:

$$i'(t) = i_x + \frac{U_a - U_{rx} - R \cdot i_x}{L}(t - t_x)$$

At point Y, at which $t = t_y$, we have:

$$i'_y = i_x + \frac{U_a - U_{rx} - R \cdot i_x}{L}(t_y - t_x) \qquad (4)$$

It has been seen above that if, at moment t_x, the rotor were abruptly stopped, which would make the voltage U_r equal to zero, the current i flowing in the coil, after that moment t_x, would follow an exponential curve of which the curve **28** is an image.

In this case, equation (2) above would become:

$$i(t) = \frac{U_a - L\frac{di}{dt}}{R} \qquad (5)$$

The same lines of reasoning as set out above show that the ordinate i''_y of the point Z disposed at $t = t_y$ on the tangent **30** to the exponential curve **28** is equal to:

$$i''_y = i_x + \frac{U_a - R \cdot i_x}{L}(\Delta t) \qquad (6)$$

in which $\Delta t = t_y - t_x$.

By substracting above equation (4) from equation (6), we have:

$$i''_y - i'_y = \frac{U_{rx}}{L}(\Delta t) \qquad (7)$$

or

-continued

$$U_{rx} = L \cdot \frac{i''_y - i'_y}{\Delta t}$$

It will be seen therefore that, at each point X on the curve **27**, the voltage U_{rx} induced in the coil by rotation of the rotor is proportional to the segment Y−Z, for a given measuring time $\Delta t = t_y - t_x$.

In particular, for $\Delta t = \tau$, U_{rx} is equal to the length of the segment Z′−Y′ in FIG. **7** in which Y′ and Z′ are the points of the tangents **29** and **30** which are located at the abscissa $(t_x + \tau)$. The ordinate of the point Z′ is equal to U_a/R which is the asymptotic value of the exponential curve **28**.

If Δt is selected at a sufficiently short value, the tangents **29** and **30** can be replaced by the curves **27** and **28**. The current i′ can by replaced by the current i_y and the current i''_y can be replaced by the current which would flow in the coil at the moment t_y if the induced voltage U_r were made equal to zero at the moment t_x.

The voltage U23 being proportional to the current which would flow in the coil after the moment t_x if the voltage induced were made zero at that moment t_x, that equation (7) set out above can be written as follows:

$$U_{rx} = J \cdot \frac{U23_y - U20_y}{\Delta t}$$

in which J is a proportionality factor which depends on the value of the resistor **18** and on the gain of the amplifier **22**, and $U23_y$ and $U20_y$ are the values of the voltages U23 and U20 at the moment t_y.

FIGS. **8***a* and **8***b* show the mode of operation of the circuit shown in FIG. **6** when the gate **21** is controlled by signal **21C** such as that shown in FIG. **8***c*.

In the present example, the gate **21** is conducting when the signal **21C** is at logic state "1" and non-conducting when the signal **21C** is at logic state "0". The control signal **21C** is formed for example by pulses having a period of 250 microseconds approximately which are at logic state "1" during some microseconds and at logic state "0" for the remainder of the time. The gate **21** therefore becomes conducting for a few microseconds every 250 microseconds, and it is non-conducting for the rest of the time.

In FIG. **8***a*, the curve **31** again represents the voltage U20 which is an image of the current i in the coil. The sawtooth curve **32** which is superimposed thereon represents the voltage U23. Whenever the gate **21** becomes conducting, that is to say when the signal **21C** is at state "1", the voltage U23 becomes equal to the voltage U20. When the gate **21** is non-conducting, that is to say when the signal **21C** is at state "0", the voltage U23 varies in accordance with a curve such as the exponential curve **28** shown in FIG. **7**.

The sawtooth curve **33** in FIG. **8***b* shows, on a different scale from that shown in FIG. **8***a*, the output voltage U22 of the differential amplifier **22**. The voltage U22 is equal to zero whenever the gate **21** is conducting and it is equal to the difference between the voltages U23 and U20 when the gate **21** is non-conducting. As the periods of time during which the gate **21** is non-conducting are equal to each other, the curve **34** which is the envelope of the curve **33** is an image of the voltage U_r induced in the coil of the motor by rotation of the rotor.

The envelope **34** could be produced by filtering the voltage U22 in a low-pass filter. The output signal of the filter could be amplified in an amplifier, the gain of which would be selected, taking into account all the proportionality factors introduced into the circuit of FIG. **6** by the choice of the resistor **18**, of the gain of the amplifier **20** and of the period of the control signal **21C**. The output signal of that amplifier would then be equal to the induced voltage U_r. However, such filtering and amplification are not necessary. The voltage U22 itself can be used directly as the measuring voltage U_m in the circuit of FIG. **4**. The voltage U_s' to which the voltage U_m is compared in the circuit **12** in FIG. **4** must obviously be selected, taking account of the above-mentioned proportionality factors.

It should be noted that the voltage U22 is independent of the supply voltage U_a since the voltage U23 and U20 are both proportional to the voltage U_a.

It has been shown above that the difference between the currents i''_y and i'_y is proportional to the voltage U_{rx} induced in the coil of the motor by rotation of the rotor at the time t_x. The FIG. 7 shows that that difference can be written as follows:

$$i''_y - i'_y = i''_y - i_x + i_x - i'_y$$

In terms of voltage, that equation can be written as follows:

$$U_z - U_y = U_z - U_x + U_x - U_y \tag{8}$$

FIG. 7 also shows that:

$$U_z - U_x = (U_a - U_x)\frac{\Delta t}{\tau}$$

Above equation (8) can therefore be written as follows:

$$U_z - U_y = (U_a - U_x)\frac{\Delta t}{\tau} + U_x - U_y \tag{9}$$

This expression shows that the voltage U_{rx} which is proportional to $(U_z - U_y)$ can be measured without measuring the voltage U_z itself.

FIG. **9** shows the basic circuit diagram of a measuring circuit **11** (see FIG. **4**) for supplying a voltage U_{m1} which is proportional to U_{rx} on the basis of equation (9) above.

In FIG. **9**, the resistor **18** for measuring the current flowing in the motor (not shown in FIG. **9**) and the amplifier **20**, the output voltage of which is an image of that current, are identical to the resistor **18** and the amplifier **20** in FIG. **6**.

The output of the amplifier **20** is connected by way of a transmission gate **61** to a first terminal of a capacitor **62** having a capacitance C62, and to the non-inverting input of a differential amplifier **63**. The second terminal of the capacitor **62** is connected to the ground of the circuit.

The output of the amplifier **63** is connected to its inverting input. The gain of that amplifier is therefore equal to one. Its output is also connected, by way of two transmission gates **64** and **65**, to the first terminals of two capacitors **66** and **67**, having capacitances C66 and C67.

The second terminal of the capacitor **66** is connected by way of a transmission gate **68** to the terminal $+U_a$ of the power supply source, and the second teminal of the capacitor **67** is connected to the output of the amplifier **20** by way of a transmission gate **69**.

The first terminal of the capacitor **66** and the second terminal of the capacitor **67** are connected to a first output terminal of the circuit, denoted by **B1**, by way of transmission gates **70** and **71** respectively. The second terminal of the capacitor **66** and the first terminal of the capacitor **67** are connected to a second output terminal of the circuit, denoted by **B2**, by way of transmission gates **72** and **73** respectively.

The gates **61** and **70** to **73** are controlled together by a signal denoted by **C1**, and the gates **64,65,68** and **69** are controlled together by a signal denoted by **C2**.

The signal **C1** and **C2** which can be supplied for example by the circuit **8** in FIG. **4** and which are shown in FIG. **10** are of identical periods of 0.5 milliseconds for example and of durations which are also identical and which are short with respect to their period, for example 30 microseconds. Each of them appears in the middle of the period of the other. FIG. **7** can also be referred to, for understanding the mode of operation of the circuit shown in FIG. **9**.

When, at a moment t_x, the signal **C1** switches the gate **61** into its conducting state, the capacitor **62** is charged to the voltage U_x which is proportional to the current i_x flowing in the coil at that moment. The voltage U_x appears at the output of the amplifier **63**. The function of the gates **70** and **73** which are also put into a conducting condition at that moment will be discussed hereinafter.

At the moment t_y, the signal **C2** switches the gates **64,65,68** and **69** into their conducting condition. The voltate U_x which is stored by the capacitor **62** and the amplifier **63** is therefore applied to the first terminal of the capacitors **66** and **67**. At the same time, the voltage U_a is applied to the second terminal of the capacitor **66** and a voltage which is proportional to the current flowing in the coil of the motor at that moment t_y is applied to the second terminal of the capacitor **67**. As the time Δt between the moments t_x and t_y is short, that voltage can be considered as being the voltage U_y in FIG. **7**. At that moment t_y, the capacitor **66** is therefore charged to a voltage $U66 = U_a - U_x$ and the capacitor **67** is charged to a voltage $U67 = U_x - U_y$.

The charges Q66 and Q67 stored in that capacitors are therefore respectively:

$$Q66 = C66(U_a - U_x)$$

and

$$Q67 = C67(U_x - U_y)$$

The following pulse **C1** switches the gates **70** to **73** into their conducting states. During that pulse **C1**, the capacitors **66** and **67** are therefore connected in parallel with the output terminals **B1** and **B2** of the circuit. The voltage U_{m1} which then appears at those terminals is equal to:

$$U_{m1} = \frac{Q66 + Q67}{C66 + C67} = \frac{1}{C66 + C67}\left[C66(U_a - U_x) + C67(U_x - U_y)\right] \tag{10}$$

If the capacitors **66** and **67** are so selected that $C66 = C67(\Delta t/\tau)$, the equation (10) above can be written as follows:

$$U_{m1} = \frac{1}{1 + \frac{\Delta t}{\tau}}\left[(U_a - U_x)\frac{\Delta t}{\tau} + U_x - U_y\right] \tag{11}$$

The expression between brackets is proportional to the voltage U_{rx} (see equation (9) above). The voltage U_{m1} is therefore also proportional to U_{rx}.

It should be noted that, with that circuit, the voltage U_{m1} which is representative of the voltage U_r induced at the moment t_x in the coil by rotation of the rotor appears at the output of the circuit only at a moment $t_x + 2\Delta t$. That delay does not cause difficulties since Δt is short.

It should also be noted that one or other of the output terminals **B1** and **B2** can be connected to the ground of the circuit, without changing the mode of operation thereof.

In the circuit shown in FIG. **6**, the accuracy of the measured value depends directly on the accuracy of the values of the resistor **24** and the capacitor **25**. It is well known that, in mass production, it is difficult to achieve a high degree of accuracy in such components. The circuit shown in FIG. **9** does not suffer from that disadvantage. The accuracy of the measured voltage depends only on the ratio between the capacitances of the capacitors **66** and **67**. Now, even in large-scale mass production, that ratio can be guaranteed, with a high degree of accuracy.

However, the circuit shown in FIG. **9** suffers from another minor disadvantage, like the circuit shown in FIG. **6**. For the purposes of making the above-indicated calculations and for following through the above-indicated lines of reasoning, it was assumed that the transistors **14** to **17** of the motor control circuit (see FIG. **6**) do not have any internal resistance when they are in a conducting condition. In actual fact, the internal resistance of the transistors is not zero and the asymptote of the exponential curves such as the curve **28** in FIG. **7** is not disposed at the ordinate U_a but at an ordinate

$$U_a' = U_a - \Sigma R_T \cdot \frac{U_a}{R + \Sigma RT}.$$

In that expression, R represents the value of the measuring resistor **18**, and ΣR_T represents the sum of the internal resistances of the transistors when conducting. As such resistances differ from one transistor to the other and are also variable in dependence on the current flowing through the transistors, the above-indicated value U_a' cannot be determined with precision.

The error in respect of measurement of the value of the voltage induced by rotation of the motor, which is caused by replacing U_a' by U_a is not very serious. Nonetheless, FIG. **11** shows the diagram of a third measuring circuit which eliminates that source of error.

All the components described with reference to FIG. **9** are also to be found in FIG. **11**, except for the gates **68** and **72** which do not appear in this circuit diagram. In addition, the second terminal of the capacitor **66** and the output terminal **B2** are directly connected to ground.

The output terminal **B1** of the circuit shown in FIG. **9** is connected to the inverting input of a differential amplifier **74**. The non-inverting input of the amplifier **74** is connected to ground. The output of the amplifier **74** is connected to its inverting input by way of a capacitor

75 connected in parallel with a transmission gate **76**. The output of the amplifier **74** is also connected through a transmission gate **77** to the non-inverting input of a differential amplifier **78**. A capacitor **79** and a transmission gate **80** are connected in parallel between the non-inverting input of the amplifier **78** and ground.

The output of the amplifier **78** forms in that example the output of the measuring circuit **11**. That output is connected to the inverting input of the amplifier **78** by way of a resistor **81** and to the ground of the circuit by way of a resistor **82**.

The non-inverting input of the amplifier **78** is also connected by way of a transmission gate **83** to the non-inverting input of a differential amplifier **84**. A capacitor **85** and a transmission gate **86** are connected in parallel between the input of the amplifier **84** and ground.

The output of the amplifier **84** is connected to its inverting input and the gain of that amplifier is therefore equal to one. Its output is also connected by way of a transmission gate **87** to a first terminal of a capacitor **88**. The other terminal of the capacitor **88** is connected to ground. Finally, the first terminal of the capacitor **88** is connected by way of a transmission gate **89** to the inverting input of the amplifier **74**.

The transmission gates **77** and **89** are controlled by the above-described signal **C1** at the same time as the gates **61**, **70**,**71** and **73**. The gates **76** and **87** are controlled by the signal **C2** which is also described above, like the gates **64**, **65** and **69**. The gates **80** and **86** are controlled by a signal **C3** which may be supplied for example by the circuit **9** for controlling the motor **10** and which is at logic state "0" during the driving pulses and at logic state "1" for the rest of the time. The gates **80** and **86** are therefore conducting between the driving pulses and non-conducting during the driving pulses. Finally, the gate **83** is controlled by a signal **C4** which is normally at logic state "0" and which goes to logic state "1" for a few microseconds about 1 millisecond after the beginning of the driving pulse. The signals **C3** and **C4** are also shown in FIG. **10**.

The mode of operation of the circuit between the output of the amplifier **20** and the terminal **B1** is identical to that of the circuit shown in FIG. **9**. However, because the second terminal of the capacitor **66** is connected to the ground of the circuit and not to the voltage U_a, the capacitor **66** is charged to the voltage $-U_x$ and not the voltage (U_a-U_x) in response to the signal **C2**. The expression for the charge Q66 therefore becomes:

$$Q66=C66\,(-U_x)$$

Above-indicated equation (11) in which the term U_a is replaced by zero shows that the voltage U_{m2} which would appear at the terminal **B1** in response to the signal **C1** if the elements **74** to **89** did not exist would be as follows:

$$U_{m2}=\frac{1}{1+\frac{\Delta t}{\tau}}\left(-U_x\frac{\Delta t}{\tau}+U_x-U_y\right) \qquad (12)$$

Comparison between that equation (12) and equation (11) above shows that:

$$U_{m2}=U_{m1}-\frac{1}{1+\frac{\Delta t}{\tau}}U_a\frac{\Delta t}{\tau}$$

It should be noted that, as long as the rotor is stationary, that is to say, between the driving pulses and at the beginning thereof, the voltage U_{m1} is zero. The voltage U_{m2r} which would appear at the terminal **B1** under those conditions would therefore be as follows:

$$U_{m2r}=-\frac{1}{1+\frac{\Delta t}{\tau}}U_a\frac{\Delta t}{\tau} \qquad (13)$$

The mode of operation of the circuit formed by the components **74** to **89** is as follows:

Between the driving pulses, the signal **C3** is at "1". The capacitors **79** and **85** are therefore short-circuited by the gates **80** and **86** which are conducting. The output of the amplifier **78**, which is output of the measuring circuit, and the output of the amplifier **84**, are at ground potential.

The capacitor **88** is discharged since the output of the amplifier **84** which is connected to ground is connected thereto at each pulse **C2** by the gate **87**.

At each pulse **C2**, the capacitor **75** is also discharged by the gate **76** which short-circuits it. Immediately after each of the pulses **C2**, the output of the amplifier **74** is therefore also at ground potential.

A moment Δt after each of the pulses **C2**, a pulse **C1** switches the gates **70**, **71**, **73**, **77** and **89** into a conducting condition. The sum of the charges contained at that moment in the capacitors **66**, **67** and **88** is therefore transferred into the capacitor **75**. The voltage **U75** at the terminals of the capacitor **75** would then be:

$$U75=-(Q66+Q67+Q88/C75)$$

if the gate **80** were not conducting. The sign − which appears in the foregoing equation is because the terminal **B1** is connected to the inverting input of the amplifier **74**.

In actual fact, the voltage **U75** remains zero as long as the signal **C3** is at state "1" and the charges **Q66** and **Q67** are transmitted to ground by way of the gate **80**. The charge **Q88** on the capacitor **88** is in any case zero at that moment. The output of the amplifier **78** therefore remains at ground potential.

At the beginning of each driving pulse, the signal **C3** goes to state "0" and remains at that state. The gates **80** and **86** are therefore non-conducting.

The above-described procedure starts again at the first pulse **C1** following the beginning of the driving pulse but this time the capacitor **79** is charged to the above-defined voltage **U75**. The gate **83** is still non-conducting, with the result that the output voltage of the amplifier **84** does not change and the capacitor **88** remains discharged. The voltage **U75** referred to above therefore becomes equal to:

$$U75=-(Q66+Q67/C75)$$

As $Q66=C66\,(-U_x)$ and $Q67=C67\,(U_x-U_y)$, the foregoing expression can be written as follows:

$$U75 = -\frac{C66(-U_x) + C67(U_x - U_y)}{C75}$$

At the moment D of the last pulse C1 preceding the pulse C4, the value of the voltage U75 is:

$$U75_D = -\frac{C66(-U_{xD}) + C67(U_{xD} - U_{yD})}{C75}$$

in which U_{xD} and U_{yD} are the values of U_x and U_y at the moment D.

The pulse C4 is produced approximately one millisecond after the beginning of the driving pulse, at a moment at which the rotor is still stationary. The pulse C4 briefly opens the gate **83**. The capacitor **85** is therefore charged to the voltage U75D which also appears at the output of the amplifier **84**. The pulse C2 following the pulse C4 opens the gate **87** and the capacitor **88** is therefore also charged to the voltage U75D. The electrical charge Q88 on the capacitor **88** therefore becomes equal to:

$$Q88 = -C88\frac{C66(-U_{xD}) + C67(U_{xD} - U_{yD})}{C75}$$

It should be noted that the capacitor **85** in practice remains charged at the voltage U75 as long as the gate **86** is non-conducting if the input resistance of the amplifier **84** is high, which is the case. The subsequent changes in the output voltage of the amplifier **74** no longer have any influence on that voltage since the gate **83** is again permanently non-conducting.

On each following pulse C1, the capacitor **88** is discharged into the capacitor **75** at the same time as the capacitors **66** and **67**. The charge on the capacitor **75** therefore becomes:

$$Q75 = Q66 + Q67 + Q88$$

It should also be noted that, at each pulse C2, the capacitor **88** is charged again to the voltage U75D which is stored by the capacitor **85**.

At any moment after the pulse C4, it is therefore possible to write the following:

$$Q75 = C66(-U_x) + C67(U_x - U_y) - C88\frac{C66(-U_{xD}) + C67(U_{xD} - U_{yD})}{C75}$$

If C88=C75, and if, as above, $C66 = C67\ (\Delta t/\tau)$, that equation becomes:

$$Q75 = C67\left(-U_x\frac{\Delta t}{\tau} + U_x - U_y + U_{xD}\frac{\Delta t}{\tau} - U_{xD} + U_{yD}\right)$$

The voltage U75, which is equal to (Q75/C75), can therefore be written as follows:

$$U75 = \frac{C67}{C75}\left(-U_x\frac{\Delta t}{\tau} + U_x - U_y + U_{xD}\frac{\Delta t}{\tau} - U_{xD} + U_{yD}\right) \tag{14}$$

The voltage U75 is independent of the voltage U_a or the voltage U_a'. In addition, it is proportional to the voltage U_{rx} induced in the coil of the motor at the moment t_x by rotation of the rotor. In fact, at the moment D defined hereinbefore, the voltage U_{m2} given by equation (12) is written as follows:

$$U_{m2} = -\frac{1}{1 + \frac{\Delta t}{\tau}}\left(U_x\frac{\Delta t}{\tau} - U_{xD} + U_{yD}\right)$$

Equation (14) above can therefore be written as follows:

$$U75 = \frac{C67}{C75}\left[-U_x\frac{\Delta t}{\tau} + U_x - U_y - \left(1 + \frac{\Delta t}{\tau}\right)U_{m2}\right] \tag{15}$$

The rotor being stationary at the moment D, the voltage U_{m2} is equal to the voltage U_{m2r} defined by the above equation (13).

By replacing the term U_{m2} in equation (15) by the value of U_{m2r} taken from equation (13) that equation (15) can be written as follows:

$$U75 = \frac{C67}{C75}\left(-U_x\frac{\Delta t}{\tau} + U_x - U_y + U_a\frac{\Delta t}{\tau}\right) \tag{16}$$

Comparison of equation (16) with equation (11) shows that:

$$U75 \doteq \frac{C67}{C75}\left(1 + \frac{\Delta t}{\tau}\right)U_{m1}$$

With the voltage U_{m1} being proportional to the voltage U_{rx}, the voltage U75 is also so proportional.

If the capacitance C75 is made equal to

$$C67\left(1 + \frac{\Delta t}{\tau}\right),$$

then $U75 = U_{m1}$.

It is clear however, that a different ratio may be selected between the capacitance C75 and the capacitances C67 and C88. Likewise, the gain of the amplifiers **74** and **84** can be different from one. In any case, the voltage U75 will remain proportional to U_{m1} and therefore to the voltage U_{rx} induced at the moment t_x in the coil of the motor by rotation of the rotor.

It should be noted that, since the non-inverting input of the amplifier **75** is connected to ground, the capacitors **66**, **67** and **88** are completely discharged into the capacitor **75** upon each pulse C1. At each pulse C2, the capacitor **75** is short-circuited by the gate **76** and the above-calculated voltage U75 falls back to zero. The capacitor **79** which is charged to the voltage U75 at each pulse C1 is provided for storing that voltage between two successive pulses C1. The voltage U75 stored by the capacitor **79** is amplified by the amplifier **78** by a factor which may be freely fixed by selection of the ratio between the values of the resistors **81** and **82**. The output voltage U78 of the amplifier **78** is also proportional to the voltage U_{rx} and may therefore form the voltage U_m applied to the comparison circuit **12** in FIG. **4**. The reference voltage U_s' which is applied in that case to the circuit **12** must obviously be selected in accordance with the characteristics of the various components of the circuit shown in FIG. **11**, in particular the capacitances of the various capacitors and the gains of the amplifiers.

FIG. **12** shows an example of a circuit for performing the function of the circuit **9**, **12** and **13** shown in FIG. **4**. In this example, the circuit **12** is formed by a separate source or by a simple voltage divider connected to the terminals of the source supplying power to the entire circuit.

In FIG. **12**, the control circuit **9** for controlling the motor **10** comprises the transistors **14** to **17** described with reference to FIG. **6**. It further comprises a D-type flip-flop **42**, the clock input Ck of which is connected to the output S**8** of the circuit **8** shown in FIG. **4**. The D input of the flip-flop **42** is connected to its inverted output Q* so that it changes state whenever the signal S8 goes from logic state "0" to logic state "1". The direct output Q of the flip-flop **42** is connected to a first input of an AND-gate **43**, the output of which is connected to the gates of the transistors **14** and **16**. The Q* output of the flip-flop **42** is connected to a first input of an AND-gate **44**, the output of which is connected to the gates of the transistors **15** and **17**.

The control circuit **9** further comprises a D-type flip-flop **45**, the clock input Ck of which is connected to the output S**8** of the circuit **8** by way of an inverter **58**.

The D input of the flop-flop is permanently at logic state "1" and the Q output thereof is connected to the second input of the gates **43** and **44**.

The calculating circuit **13** comprises a flip-flop **46** which is also of D type and the clock input Ck of which is connected to the output S**8** of the circuit **8**, while the D input thereof is permanently at logic state "1". The Q and Q* outputs of the flip-flop **46** are respectively connected to the first inputs of two AND-gates **47** and **48**, the second inputs of which are both connected to the Q output of the flip-flop **45**.

The resetting input R of the flip-flop **46** is connected to the output of the differential amplifier **41**.

Three transmission gates **49**, **50** and **51** have their control inputs respectively connected to the outputs of the gates **47** and **48** and to the Q* output of the flip-flop **45**. The gates **49**, **50** and **51** are similar to the gate **21** in FIG. **6**. When their control input is at logic state "0", they are in their non-conducting condition while when their control input is at logic state "1", they are in their conducting condition.

The gate **49** is connected between the positive terminal $+U_a$ of the power source and a resistor **52** having a resistance R52.

The gate **50** is connected between the negative terminal $-U_a$ of the power source and a resistor **53** having a resistance R53.

Finally, the gate **51** is connected between a voltage U_b which will be defined hereinafter and a resistor **54** having a resistance R54.

The second terminals of the the resistors **52**, **53** and **54** are connected together and to the inverting input of a differential amplifier **55**, the non-inverting input of which is connected to a given voltage, which is that of ground in the present example.

A capacitor **56** having a capacitance C56 is connected between the common point of the resistors **52** to **54** and ground.

The output of the amplifier **55** is connected to a first input of an AND-gate **57**, the second input of which is connected to the Q* output of the flip-flop **46**. The output of the gate **57** is connected to the resetting input R of the flip-flop **45**.

The mode of operation of this circuit will now be described with reference to the diagram shown in FIG. **13**. In the rest condition, the Q outputs of the flip-flops **45** and **46** are at state "0". The outputs of the gates **43**, **44**, **47** and **48** are therefore also at "0". The transistors **14** and **15** are therefore conducting, which short-circuits the coil of the motor **10**. The transistors **16** and **17** are non-conducting. The gates **49** and **50** are non-conducting while the gate **51** is put into its conducting condition by state "1" present at the Q* output of the flip-flop **45**.

The voltage U**56** at the terminals of the capacitor **56** is therefore equal to the voltage U_b. If that voltage is positive, as in this example, the outputs of the amplifier **55** and the gate **57** are at "0".

If the voltage U_b is negative, the output of the amplifier **55** and the output of the gate **57** are at "1".

As the rotor of the motor **10** is stationary, the voltage U22 is zero and the output of the amplifier **41** is at "0".

For the purposes of the present explanation, it will be assumed that the Q output of the flip-flop **42** is at "0" for the moment and that the output signal S**8** of the circuit **8** goes to state "1" for a few microseconds whenever the motor is to advance by one step.

As soon as the signal S**8** goes to state "1", at the moment t**0**, the Q outputs of the flip-flops **42** and **46** go to state "1".

The output of the gate **57** therefore goes to state "0", even if the output of the amplifier **55** is at state "1" at that moment.

When the signal S**8** goes to "0" again, a few microseconds later, the Q output of the flip-flop **45** also goes to state "1".

The output of the gate **43** therefore also goes to state "1". The transistor **14** is non-conducting and the transistor **16** is switched into the conducting condition. The current i begins to flow in the coil of the motor **10**, through the transistors **15** and **16**. The voltage at point **19** begins to rise and to act on the measuring circuit **11**, as described above with reference to FIGS. **6**, **9** or **12**.

At the same time, the Q* output of the flip-flop **45** goes to state "0", which causes the gate **51** to become non-conducting. The output of the gate **47** goes to state "1", which switches the gate **49** into a conducting condition. The voltage $+U_a$ is therefore applied to the capacitor **56** by way of the resistor **52** and the voltage U**56** begins to rise on an exponential curve having a time constant $\tau 1$ which ist determined by the product R52·C56. In order to simplify the drawing, the variation in the voltage U**56** is shown in FIG. **13** as a linear variation.

When, at moment t_d, the voltage U**22** exceeds the threshold voltage Us', the output of the amplifier **41** goes to state "1". The Q output of the flip-flop **46** therefore goes back to state "0", which causes the gate **49** to become non-conducting. The value U_d attained by the voltage U**56** at the moment t_d depends on the time T2 taken by the induced voltage U_r to reach the threshold voltage U_s, on the value of the voltage U_b and on the time constant $\tau 1$.

At the same moment t_d, the Q* output of the flip-flop **46** goes to state "1", which switches the gate **50** into a conducting condition. The voltage $-U_a$ is therefore now applied to the capacitor **56** by way of the resistor **53**. The voltage U**56** therefore begins to fall, from the value U_d, with a time constant $\tau 2$ which is determined by the product R53·C56.

When, a moment t_i, the voltage U56 becomes equal to a given voltage which is the voltage of ground in the present example, the output of the amplifier **55** goes to state "1", which switches the flip-flop **45** into its rest condition, that is to say, with its Q output at "0" and its Q* output at "1". The output of the gate **43** therefore goes back to state "0", which switches the transistor **16** into a non-conducting condition and causes the transistor **14** to conduct. The current i is therefore interrupted and the rotor of the motor terminates its stepping motion by virtue of its inertia and by virtue of a part of the energy which is stored in the form of magnetic energy in the inductance of the coil. The rotor is braked by the short-circuit which occurs through the transistors **14** and **15**.

The time T3 taken t_y the voltage U56 to become equal to zero depends on the voltage U_d that it has attained at the moment t_d and on the time constant $\tau 2$.

The duration T1 of the driving pulse is equal to the sum of the durations T2 and T3. As T3 depends on the voltage U_d and as that voltage U_d itself depends on the duration T2, it will be seen that the duration T1 directly depends on the time T2 taken by the voltage U_r induced in the coil of the motor by rotation of the rotor to reach a predetermined value U_s.

As the duration T01 of the driving pulse required to cause the motor to rotate without load, the time T02 taken by the induced voltage U_r to reach the value U_s when the motor is also without load, and the coefficient a and b of the straight lines which represent the variation in dependence on the load of the motor of the duration of the driving pulse and of the time taken by the voltage U_r to reach the threshold U_s are known by means of tests, as described hereinbefore, it is easy to determine the time constants $\tau 1$ and $\tau 2$ and the voltage U_b in such a way as to verify the above-mentioned relationship (1). It is therefore in the form of those parameters $\tau 1$, $\tau 2$ and U_b that the constants k and K in the relationship (1) are introduced in the present embodiment of the calculating circuit **13**. The voltage U_b can be selected as a negative voltage, if necessary, to take account of the sign of the constant K.

At the moment t_i, the state "0" of the Q output of the flip-flop **45** causes the gate **50** to be in a non-conducting condition. The state "1" of the Q* output of the flip-flop **45** switches the gate **51** into a conducting condition. The voltage U_b is therefore again applied to the capacitor **56** through the resistor **54**. The voltage U56 therefore rises again until, after a certain period of time, it reaches the voltage U_b.

As soon as the voltage U56 becomes positive again, the output of the amplifier **55** goes back to state "0". That output therefore remains at state "1" only for a very short time.

A certain time after the moment t_d, the voltage U22 falls back below the voltage U_s'. The output of the amplifier **41** therefore goes back to state "0". That period of time, which does not play any part in operation of the circuit, depends on the mechanical load which is driven by the motor and the value of the voltage U_s'.

When the signal S8 goes again to "1", the above-described procedure begins again, with the only difference that this time, it is the Q* output of the flip-flop **42** and therefore the output of the gate **44** which go to state "1". The transistor **15** becomes non-conducting and the transistor **17** conducting, causing the current i to flow in the direction opposite to its direction of flow in the previous situation.

FIG. **14** shows another embodiment of a circuit for performing the function of the calculating circuit **13** shown in FIG. **4**.

The circuit shown in FIG. **14** comprises a D-type flip-flop **91**, the clock input Ck of which receives the output signal S8 of the circuit **8** shown in FIG. **4**. The D input of the flip-flop **91** is permanently at logic state "1". Its Q output is connected to the U/D input of an up-down counter **92**. The logic state "1" or "0" of that input U/D determines whether counter **92** is incremented or decremented by pulses it receives on its input Ck as described hereinafter. The counter **92** is also preselectable, which means that, in response to a pulse at a control input C, the content thereof assumes a value which is determined by logic states "0" or "1" which are applied to preselection inputs generally denoted by P.

The control input C of the counter **92** is also connected to the output S8 of the circuit 8 and its inputs P are connected, in a fixed or modifiable manner which will be described hereinafter, to the potentials representing logic states "0" and "1".

The clock input Ck of the counter **92** is connected to the output of an OR-gate **93**, the inputs of which are respectively connected to the outputs of two AND-gates **94** and **95**.

The inputs of the gate **94** are respectively connected to the Q output of the flip-flop **45** in FIG. **12** (not shown in FIG. **14**), to the Q output of the flip-flop **91** and to a circuit (also not shown) which supplies a periodic signal at a frequency f1. That circuit may be the circuit **8** shown in FIG. **4** and the frequency f1 is selected in a manner to be described hereinafter.

The inputs of the gate **95** are respectively connected to the Q output of the flip-flop **45**, the Q* output of the flip-flop **91** and to a circuit which may also be the circuit **8** shown in FIG. **4** and which produces a periodic signal at a frequency f2, the choice of which will also be described hereinafter.

The outputs of the counter **92**, which are generally denoted by S, are connected to a detecting circuit **96**, the output of which is at state "1" when the content of the counter **92** is equal to zero. The circuit **96** may be simply formed by an inverted OR-gate, each input of which is connected to an output of the counter **92**.

The output of the circuit **96** is connected to an input of an AND-gate **97**, the other input of which is connected to the Q* output of the flip-flop **91**.

Finally, the output of the gate **97** is connected to the resetting input R of the flip-flop **45** shown in FIG. **12** (but not shown in FIG. **14**).

The mode of operation of this circuit, which is illustrated in FIG. **15**, is as follows:

When the signal S8 goes to state "1", the content N of the counter **92** assumes a value N_i which is imposed thereon by the state of its inputs P. At the same time, the Q output of the flip-flop **91** goes to state "1".

When, at the end of the pulse S8, the Q output of the flip-flop **45** goes to state "1", the pulses at a frequency f1 pass through the gates **94** and **93** and begin to increment the content of the counter **92**, starting from the value N_i that the counter content assumed in response to the signal S8.

At the end of the period of time T2', the induced voltage measured by the circuit **12** reaches the value of the reference voltage and the output S12 goes to state

"1". The Q output of the flip-flop **91** therefore goes to state "0" and its Q* output goes to state "1".

The value N_d of the content of the counter **92** at that moment depends on the time T2′ taken by the induced voltage U_r to reach the threshold voltage U_s, the initial value N_i assumed by the content of the counter **92** in response to the signal **S8**, and the frequency f1.

With the Q* output of the flip-flop **91** being maintained at state "1", the pulses at a frequency f2 pass through the gates **95** and **93** and begin to decrement the content of the counter **92**, from the above-indicated value N_d.

When the content of the counter **92** reaches the value zero, the output of the detecting circuit **96** and the output of the gate **97** go to state "1", which sets the Q output of the flip-flop **45** to "0". The driving pulse which had begun at the end of the signal S8 is thus interrupted.

The time T3′ taken by the counter **92** to reach the state zero depends on the value N_d which is reached by the counter content at the moment at which the output **S12** of the circuit **12** goes to state "1", and the frequency f2.

In a similar manner to the situation shown in FIG. **13**, the duration T1′ of the driving pulse is equal to the sum of the durations T2′ and T3′. As the duration T3′ depends on the value N_d and as that value N_d itself depends on the duration T2′, the duration T1′ of the driving pulse depends directly on the time T2′ taken by the voltage U_r induced in the coil of the motor by rotation of the rotor to reach the predetermined value U_s.

In this caşe, the frequencies f1 and f2 play the part of the time constants $\tau 1$ and $\tau 2$ of the embodiment shown in FIG. **12**, and the initial value N_i plays the part of the voltage U_b.

The frequencies f1 and f2 and the initial value N_i must therefore be determined by the same tests as those required for determining the time constants $\tau 1$ and $\tau 2$ and the voltage U_b in the embodiment shown in FIG. **9**, in order for the above-mentioned relationship (1) to be verified. It is in the form of the frequencies f1 and f2 and the initial value N_i that the constants k an K of relationship (1) are introduced in this embodiment of the calculating circuit **13**.

If necessary, depending on the sign of the constant K, a negative initial value N_i should be introduced into the counter **92**. As the value of the content of a counter is always a positive number, in this case an initial value N_i' which is equal to the difference between the counting capacity of the counter **92** and the absolute value of N_i must be introduced into the counter.

In this case, the content of the counter **92** passes through zero after N_i pulses at a frequency f1 have been received by its input Ck. However, as the Q* output of the flip-flop **91** is still at state "0" at that moment, the signal "1" supplied by the output of the circuit **96** is blocked by the gate **97**. The drive pulse is therefore not interrupted at that moment.

It will be appreciated that the above-described circuit only constitute examples of circuits for carrying the invention into effect. Other circuits for measuring the voltage U_r could be designed. Likewise, the information provided by the measurement operation could be utilised in a different manner. Finally, even where the above-mentioned information is supplied by the time taken by the voltage U_r to exceed a given threshold U_s, the calculating circuit **13** could be of a different design. However, these differences in the mode of performing the invention would not constitute a departure from the scope thereof.

It should also be noted that it would be possible for the relationship (1) between the minimum duration of the drive pulse and time T2 taken by the voltage U_r to exceed the threshold voltage U_s not to be linear. However, even in that case, it could be defined by a few tests.

The calculating circuit **13** would simply have to be designed in such a way as to perform the desired function.

What we claim is:

1. A method for determining the voltage induced in a stepping motor winding by the rotation of the stepping motor rotor comprising:

determining the actual current flowing through said winding;

determining the theoretical current which would flow through said winding at a second instant if said induced voltage were zero since a first instant anterior to said second instant, said first and second instants being separated by a determined time interval; and

determining the difference between said theoretical current and the actual current at said second instant;

whereby said difference is proportional to the value of said induced voltage at said first instant.

2. The method of claim **1** wherein said theoretical current and said difference are periodically determined with a period equal to or longer than said time interval.

3. The method of claim **1** wherein said actual current is determined by producing a first voltage proportional to said actual current, said theoretical current is determined by producing a second voltage the value of which increases exponentially between said first and second instants from a value equal to the value of said first voltage at said first instant with a time constant equal to the time constant of said winding, and producing a third voltage the value of which is equal to the difference between the values of said second and first voltages at said second instant said third voltage being proportional to said difference.

4. A method for determining the voltage induced in a stepping motor winding by the rotation of the stepping motor rotor in response to a supply voltage applied to said winding comprising:

producing a first voltage proportional to the current flowing through said winding;

storing the value of said first voltage at a first instant;

producing a second voltage the value of which is equal to the difference between said stored value and the value of said first voltage at a second instant subsequent to said first instant, said first and second instants being separated by a determined time interval;

producing a third voltage the value of which is equal to the difference between the value of said supply voltage and said stored value; and

producing a fourth voltage the value of which is equal to the sum of said second voltage and of the product of said third voltage by the quotient of said time interval by the time constant of said winding;

whereby said fourth voltage is proportional to the value of said induced voltage at said first instant.

5. The method of claim **4** wherein said storing and said producing a second voltage are periodically performed with a period equal to or greater than said time interval.

6. A method for determining the voltage induced in a stepping motor winding by the rotation of the stepping motor rotor in response to a supply voltage applied to said winding comprising:

producing a first voltage proportional to the current flowing in said winding;

sampling said first voltage at each instant of a plurality of instants separated by a determined time interval, said plurality comprising a first and a second instant separated by said time interval, both situated between the application of said supply voltage and the beginning of said rotation;

producing a correction voltage in accordance with the following equation:

$$U_c = U_{xD}\left(\frac{\Delta t}{\tau} - 1\right) + U_{yD}$$

where:

U_c is said correction voltage;

U_{xD} is said sampled voltage at said first instant;

U_{yD} is said sampled voltage at said second instant;

Δt is said time interval and

τ is the time constant of said winding; producing at each instant of said plurality following said second instant an uncorrected measuring voltage in accordance with the following equation:

$$U_u = U_x\left(\frac{\Delta t}{\tau} - 1\right) + U_y$$

where:

U_u is said uncorrected measuring voltage;

U_x is said sampled voltage at the instant preceding immediately said each instant following said second instant; and

U_y is said sampled voltage at said each instant following said second instant; and

producing at said each instant following said second instant a corrected measuring voltage by subtracting said uncorrected measuring voltage from said correction voltage;

whereby said corrected measuring voltage is proportional to said induced voltage at said instant preceding immediately said each instant following said second instant.

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